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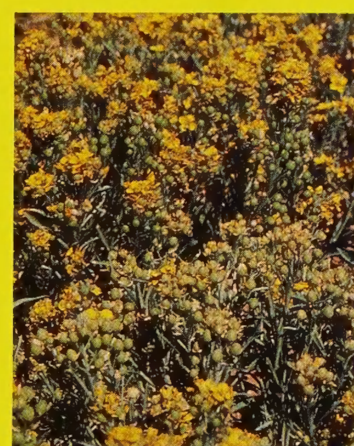
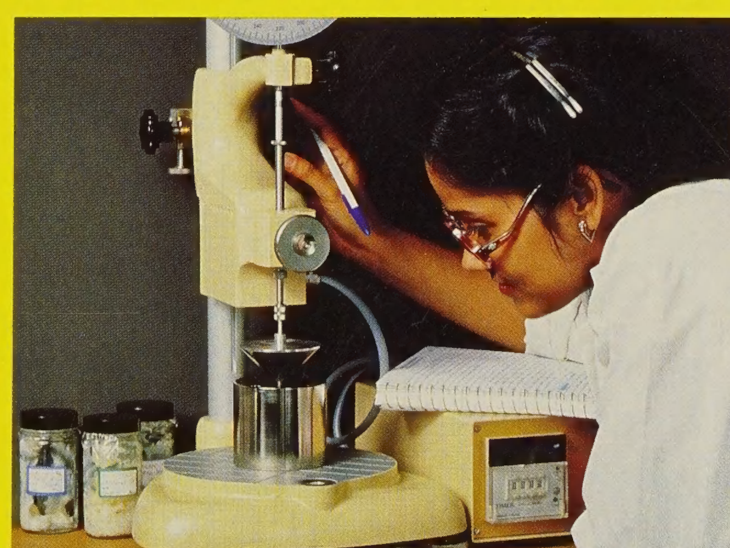
Lesquerella as a Source of Hydroxy Fatty Acids for Industrial Products





Growing Industrial Materials Series

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Lesquerella as a Source of Hydroxy Fatty Acids for Industrial Products

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Cooperative State Research Service,

in conjunction with the

Agricultural Research Service,
Economic Research Service, and
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Growing Industrial Materials Series

Abstract

The Assistant Deputy Administrator for Special Programs, Cooperative State Research Service (CSRS), U.S. Department of Agriculture (USDA), appointed a task force to assess the potential of lesquerella as an industrial oilseed crop. In addition to the chairman from CSRS, staff from USDA's Agricultural Research Service (ARS) and Economic Research Service (ERS) served on the task force, along with personnel from the University of Missouri.

The task force evaluated the current status of lesquerella research and used a Delphi survey to seek information on lesquerella from knowledgeable individuals in the private and public sectors. No insurmountable barriers to commercialization were identified; numerous hindrances can be overcome with additional research and development. This report summarizes the findings of the task force and provides recommendations for developing and commercializing lesquerella as a source of hydroxy fatty acids for industrial products.

Acknowledgments

The task force wishes to acknowledge Paul O'Connell and Daniel Kugler of CSRS's Special Programs for initiating this assessment. We also wish to thank Raymond Brigham of Texas A&M University and Robert Vignolo of the International Castor Oil Association for sharing their knowledge of castor production and uses. In addition, we want to express our gratitude to survey respondents who helped delineate opportunities, hindrances, and research and development needs for lesquerella commercialization.

Cover photographs

Upper left: close up of a lesquerella flower. Upper middle: lesquerella in bloom with some seed pods already formed. Upper right: lesquerella being harvested with a small grain combine. Lower left: expeller processing oil from lesquerella seed at the Jojoba Growers & Processors, Inc., plant, Apache Junction, Arizona. Lower right: Alka Chaudhry of the Agricultural Research Service, National Center for Agricultural Utilization Research, conducting a grease penetration test on a lubricating grease made from lesquerella oil fatty acids.

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Various plant species of the genus *Lesquerella* have the potential to provide U.S. farmers with a new crop and U.S. industry with a domestic source of hydroxy fatty acids. To assess lesquerella's prospects as a new crop, a USDA-led task force evaluated the current status of lesquerella research and development and gathered information on lesquerella from knowledgeable individuals in the public and private sectors using a Delphi survey. Both opportunities and challenges for commercialization exist. However, none of the hindrances appear insurmountable. The greatest impediment is a lack of resources devoted to crop and product development.

Lesquerella is only 6 years out of the wild. Remarkable agronomic progress has occurred. Plant selection research has increased average yields in experimental plots from the equivalent of about 1,000 pounds per acre to over 1,800 pounds. Current production and crushing equipment can be used to grow and process lesquerella. The resulting oil and meal can provide raw materials for industrial and agricultural products. Because of their special chemical attributes, the oil and its derivatives can be used in a wide range of products, including resins, waxes, nylons, plastics, high-performance lubricants, corrosion inhibitors, cosmetics, and coatings. The meal can be used as cattle feed.

Researchers are not the only ones excited about the prospects of lesquerella. Industry has noted the progress in crop production research and the current and potential uses of hydroxy fatty acids in manufacturing. As a result, several firms have joined USDA in development efforts.

Hydroxy Fatty Acids

Hydroxy fatty acids are a special kind of fatty acids that have a hydroxyl group (an oxygen and hydrogen) attached to the carbon chain. Presently, castor oil and its derivatives are the only commercial source of these industrial fatty acids. Two castor oil derivatives, ricinoleic and sebacic acids, are listed as strategic and critical materials by the Department of Defense. Yet, since the early 1970s, all of the castor oil used in this country has been imported. During the past 30 years, U.S. imports have ranged from 29,347 to 64,351 metric tons.

Researchers have identified three hydroxy fatty acids—lesquerolic, densipolic, and auricolic acids—as the primary fatty acids in the seed oils of lesquerella species. Within a species, usually one acid predominates over the other two. All three are similar to ricinoleic acid, the dominant fatty acid in castor oil.

The Crop

Agronomic research on lesquerella has focused on plant selection, planting methods, irrigation, and harvesting. Despite an annual commitment to the crop of less than one-half scientist year, excellent progress toward commercialization has been achieved. (A scientist year is the time of one scientist working full time for a year.)

Of the 23 lesquerella species evaluated, *L. fendleri* has the best agronomic potential. It is a winter annual, native to the Southwest. *L. fendleri* seed contains over 25 percent oil, by weight, and about 55 percent of that is lesquerolic acid.

Considerable genetic variation has been observed both within the genus and in *L. fendleri*, which appears to be highly cross-pollinated. These characteristics will provide plant breeders with opportunities to improve the oil content of the seed and the amount of hydroxy fatty acids in the oil, as well as yield, an erect growth habit, and other traits needed in a commercial oilseed crop.

Preliminary results from crop production research in Arizona indicate that lesquerella can be grown in a cropping system very similar to that used for winter wheat or other small grains. Many farmers already own the equipment for planting and harvesting; minor modifications may be needed to handle the small seed.

Processing

Several laboratory and pilot-scale experiments have evaluated existing oilseed processing methods to extract lesquerella oil and refine it. Various processes could be used, but results suggest that extrusion followed by full solvent extraction would be the optimum procedure for noncosmetic uses. Flaked lesquerella seed forms good collets and a high percentage of the oil is recovered by solvent extraction.

Following extraction, oils are usually subjected to further refining, such as degumming and bleaching. Limited laboratory experiments have attempted to remove the distinct reddish color from crude lesquerella oil with charcoal and bleaching clays. In addition to further bleaching studies, more research is required to determine the extent of degumming and refining needed to meet specific product standards.

Lesquerella seed contains glucosinolates, as do the seeds from other native plants of the *Brassicaceae* (mustard) family. These sulfur-containing glucose compounds usually remain in the meal after the seed is crushed. However, small amounts may appear in the oil and can interfere with some chemical reactions during manufacturing.

Lesquerella meal also contains an enzyme—thioglucosidase—that converts glucosinolates into unpalatable and antinutritional compounds that may adversely affect swine and poultry. Ruminants, such as cattle, exhibit much greater tolerance.

For cattle feed, the best way to maintain the quality of the meal is to inactivate the enzyme during processing, thereby preventing the breakdown of the glucosinolates. Research has demonstrated that this can be done in either cookers or extruders that prepare seed for oil extraction.

Products

Preliminary analysis has compared lesquerella and castor oils. Further research is needed to validate the functionality of lesquerella oil derivatives, not only in the laboratory but also in commercial applications. A high priority would be to demonstrate the similarities and differences of ricinoleic and lesquerolic acids. Where higher molecular weights and position of functional groups are important for chemical properties of the products, lesquerolic acid could be superior.

Twenty to 36 percent of *L. fendleri* oil is composed of oleic, linoleic, and linolenic acids in roughly a two-one-two ratio. These acids are commonly found in other fats and oils used for animal feeds and industrial raw materials. Researchers, processors, and manufacturers are faced with the challenge of finding ways to economically separate lesquerolic acid from these other fatty acids. Income from their sale will help offset separation costs.

Lesquerella meal is a good candidate for use as a protein supplement in livestock rations, primarily for beef cattle. It contains 30 to 35 percent protein. Scientists have analyzed the meal of 14 lesquerella species, and *L. fendleri* meal was one of the best in terms of its amino acid content and balance.

Based on the prices of similar oils and meals, the value of lesquerella seed is estimated to be about 15 cents per pound. With yields of 1,800 to 2,000 pounds per acre, lesquerella could be worth $270 to $300 per acre. In Arizona, preliminary cash operating expenses for lesquerella are estimated to be $222 per acre, slightly lower than those for irrigated durum wheat.

PMC System and Delphi Results

The task force used a production/marketing/consumption (PMC) system to examine the commercial potential of lesquerella. The group evaluated the technical, economic, and institutional aspects of crop production, marketing—including procurement, processing, and product distribution—and product consumption. A Delphi survey was used to gather information on lesquerella's level of development. (See the section "Delphi Survey" for a description of the methodology.) No insurmountable barriers to commercialization were identified by the survey respondents. However, many opportunities for improvement exist.

Overall, respondents perceived the production subsystem as less constrained than the marketing and consumption subsystems. Within the production subsystem, the majority of components were rated as having moderate constraints. Most of these impediments can be overcome with further research. Economic hindrances were more noticeable than technical barriers. Respondents rated land allocation, production financing, and research funding as highly constraining factors. No institutional factors were perceived as major hindrances, although concern was expressed about the lack of approved pesticides.

Within the marketing subsystem, lack of a procurement network and a dependable supply of lesquerella seed were viewed as technically constraining. Respondents perceived four components as highly constrained by economic factors: competitive procurement procedures, a dependable seed supply, and expenditures by research and development institutions for new product applications and for market establishment. Nearly all marketing components were rated as having at least moderate economic impediments. No specific regulations or institutional barriers were identified. However, the lack of market information on the relationship between lesquerella and castor feedstocks was considered as highly constraining.

Little research has been conducted on the consumption subsystem. Therefore, respondents rated all components as moderately to highly constrained. End-product competition was cited as a major barrier, both technically and economically. To compete, lesquerella products must exhibit an advantage over other raw materials.

Research Recommendations

Additional resources can be fruitfully employed to enhance lesquerella's commercial prospects. Public sector research and development, plus cooperative private sector involvement, are needed to move lesquerella toward the marketplace. The task force recommends emphasis on the following research and development activities (no priority intended):

- Collect and evaluate lesquerella germplasm.
- Increase seed yields, the percentage of oil in the seed, and the hydroxy fatty acid content of the oil.
- Refine cultural practices for producing the crop, such as planting methods and fertilizer and water management.
- Obtain label approval to use pesticides for weed and insect control as part of an integrated pest management program.
- Optimize oil extraction processes.
- Study refining and bleaching of the oil.
- Expand product research and development to take advantage of oil's functional attributes.
- Conduct further experiments with lesquerella meal to determine its nutritional and economic value, measure animal performance, and obtain approval from the Food and Drug Administration for use as a feed ingredient in interstate commerce. Meal from both expeller and solvent extraction processes should be evaluated.
- Define the economics of lesquerella production and marketing.
- Develop systems to provide producers, processors, and manufacturers with pertinent market information for seed, meal, oil, and fatty acids.
- Form public-private demonstration projects to promote lesquerella commercialization.

Needed Resources

Based on the potential identified in this assessment, the task force recommends a significant increase in resources for lesquerella. We urge that 4.5 new scientist years (SYs) be devoted to lesquerella development for the next 5 years, with annual funding of $800,000. The task force is confident that significant progress can be made at this level of support. The investment will yield good dividends to investors, be they public or private.

Two SYs should be devoted to plant improvement and development of cultural and management practices. Two SYs should be allocated to product development research on items like greases, lubricants, chemical intermediates, and polymers. One-half SY should support marketing, infrastructure development, and formation of public-private sector partnerships.

Cultivating precommercial cooperative activities among government, academia, and private industry is necessary. Often, such cooperative efforts require all parties to contribute technical and financial resources. As evidence of private sector interest in lesquerella, two firms have joined USDA and the University of Arizona in a cooperative agreement to grow 20 acres in 1990-91 to obtain sufficient amounts of oil for initial product testing. Recently, a cosmetics firm expressed interest in purchasing commercial quantities of oil in 1993.

• • Introduction • •

Plants from various species of the genus *Lesquerella* have been cited as prime candidates for new crop development as a source of hydroxy fatty acids [1, 2, 3, 4]. Presently, imported castor oil and its derivatives are the only commercial source of these industrial fatty acids. Ricinoleic and sebacic acid, two of the castor derivatives, are classified by the Department of Defense (DOD) as strategic and critical materials.

Besides its distinctive fatty acid content, lesquerella possesses other positive features. Many farmers already own the equipment for planting and harvesting; minor modifications may be needed to handle the small seed. It could replace small grains in various crop rotations. In addition, existing oilseed facilities are capable of crushing lesquerella seed into oil and meal. The oil contains over 50 percent hydroxy fatty acids, while the meal has over 30 percent protein and a good amino acid balance.

The United States has excess agricultural capacity [5, 6] that might be more fully utilized by producing industrial raw materials [7, 8]. Concerns for diminishing petroleum reserves, trade imbalances, the environment, and rural economies also highlight the need for additional efforts to develop and commercialize nonfood and nonfeed uses of agricultural commodities [9].

ARS plant scientists Anson Thompson and David Dierig inspecting lesquerella plots.

Some potential benefits from developing lesquerella include:

- creating a reliable, domestic source of hydroxy fatty acids,
- developing new industrial products from renewable raw materials,
- expanding market opportunities for farmers, and
- providing economic opportunities for rural communities.

For lesquerella to be a commercial success, production of the crop, processing of the seed, and manufacture of the products must all be money-making ventures. Impediments in one of these segments, such as low yields or high processing costs, can preclude successful commercialization.

However, profitable production is only one side of the issue. As ingredients in chemical manufacturing or animal feeds, lesquerella oil and meal will need an advantage to induce buyers to supplement or switch from their current raw materials. Lower costs, better quality or availability, improved performance, new and novel uses relative to existing materials, or a combination of these qualities may provide that advantage.

To assess lesquerella's potential as a new crop, the Assistant Deputy Administrator for Special Programs of USDA's Cooperative State Research Service (CSRS) appointed a task force of key individuals. Members were from CSRS, the Agricultural Research Service (ARS), the Economic Research Service (ERS), and the University of Missouri.

The task force evaluated the technical, economic, and institutional feasibility of producing, processing, and marketing lesquerella. Uses of the hydroxy fatty acids, as well as lesquerella's other fatty acids and meal, were examined.

The task force attempted to identify both hindrances to, and strategies for, commercializing lesquerella. To help with this endeavor, a Delhi survey gleaned information from people involved with lesquerella, castor, and other new crops. (The Delphi methodology uses iterative questionnaires to gather expert opinion.) Individuals from both the private and

public sectors contributed. Based on the accumulated information, the task force identified research and development needs to foster commercialization.

This report presents the findings of the task force. A discussion of hydroxy fatty acids is followed by sections on the current status of research on lesquerella production, processing, products, and economics. The results of the Delhi survey precede recommendations for further research and development.

Hydroxy Fatty Acids

Fatty acids are the building blocks of all vegetable oils. They are composed of chains of carbon atoms. Examples include oleic and linoleic acids, the common fatty acids found in edible oils, such as soybean, olive, corn, and sunflower.

Not only are vegetable oils used in cooking and food products, they have many industrial uses. For example, between October 1988 and September 1989, 282 million pounds of soybean oil were used in paints, varnishes, resins, plastics, and other manufactured products [10]. (About 949,000 acres of soybeans were needed to produce this amount of oil.)

The chain length and chemical reactivity of a fatty acid help determine its value for industrial purposes. Some fatty acids have chemical attributes that add to their value, such as hydroxyl groups. The hydroxyl group (an oxygen and hydrogen) gives a fatty acid special properties, such as higher viscosity and reactivity compared with other fatty acids.

The primary fatty acids in lesquerella oil are hydroxy fatty acids. In the various species studied, researchers have identified three distinct types of hydroxy fatty acids—lesquerolic, densipolic, and auricolic acids [11, 12, 13, 14, 15, 16]. They are similar to ricinoleic acid, the dominant fatty acid in castor oil [17].

Like ricinoleic acid, lesquerella's hydroxy fatty acids have hydroxyl groups, double bonds, and carboxyl groups (CO_2H) that provide sites where chemical reactions can occur (figure 1). However, lesquerolic and auricolic acids each have 20 carbons, whereas ricinoleic and densipolic possess only 18. Densipolic and auricolic acids have two double bonds, making them more reactive than either ricinoleic or lesquerolic acid.

Figure 1. Chemical Structure of Ricinoleic Acid from Castor Oil and Lesquerolic, Densipolic, and Auricolic Acids from Lesquerella Oil.

Ricinoleic acid (18 carbon chain, one double bond)	$CH_3(CH_2)_5\text{-}\overset{\text{OH}}{CH}\text{-}CH_2\text{-}CH{=}CH\text{-}(CH_2)_7CO_2H$
Lesquerolic acid (20 carbon chain, one double bond)	$CH_3(CH_2)_5\text{-}\overset{\text{OH}}{CH}\text{-}CH_2\text{-}CH{=}CH\text{-}(CH_2)_9CO_2H$
Densipolic acid (18 carbon chain, two double bonds)	$CH_3CH_2\text{-}CH{=}CH\text{-}(CH_2)_2\text{-}\overset{\text{OH}}{CH}\text{-}CH_2\text{-}CH{=}CH\text{-}(CH_2)_7CO_2H$
Auricolic acid (20 carbon chain, two double bonds)	$CH_3CH_2\text{-}CH{=}CH\text{-}(CH_2)_2\text{-}\overset{\text{OH}}{CH}\text{-}CH_2\text{-}CH{=}CH\text{-}(CH_2)_9CO_2H$

Source: [17].

Because of their special chemical attributes, hydroxy fatty acids are used in a wide range of products, including resins, waxes, nylons, plastics, corrosion inhibitors, cosmetics, and coatings. Furthermore, they are used in grease formulations for high-performance military and industrial equipment. These latter uses have prompted DOD to include ricinoleic and sebacic acids, which are derivatives of castor oil, in their stockpile of strategic and critical materials. (For additional information on castor oil uses, see appendix A.)

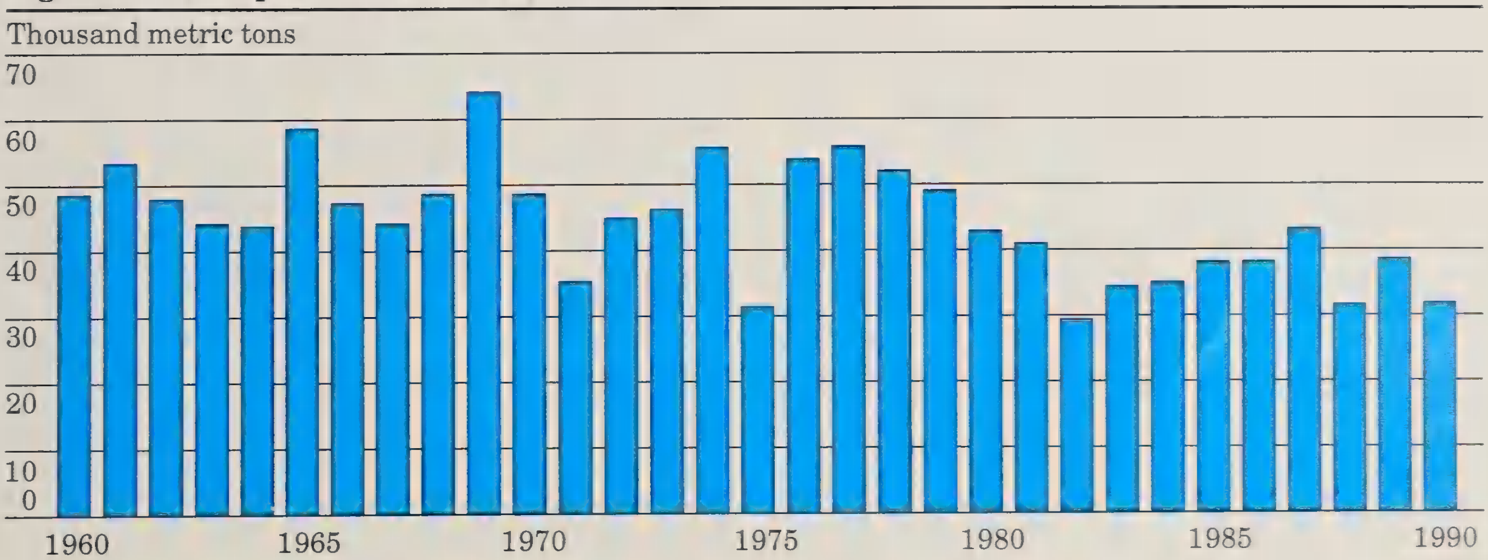
Since the early 1970s, all of the castor oil used in this country has been imported. World production fluctuates from year to year because most castor is grown under dryland conditions in developing countries [18]. During the past 30 years, U.S. imports have ranged from 29,347 to 64,351 metric tons (figure 2). Brazil and India are our primary suppliers [19].

Because of fluctuating supplies, world prices for castor oil vary considerably. This has hindered its use in domestic manufacturing. Between 1972—when castor production ceased in the United States—and 1990, annual average wholesale prices for castor oil ranged from a low of 23.3 cents per pound in 1972 to a high of 72.7 cents in 1984. Even within a year, average monthly prices often varied by more than 25 percent [18].

Supply and price instability impose severe handicaps on users. They impact cash flow, make corporate planning difficult, and discourage investment in new products. In fact, some companies have sought alternative raw materials, primarily petroleum-based feedstocks.

The task force believes that new uses can be developed for lesquerella oil and it could complement castor oil in some uses as a source of hydroxy fatty acids. Industry-led efforts are underway to reintroduce castor as a U.S. crop [18]. Domestic supplies would not depend on a single crop. The two would be grown in different seasons; lesquerella is planted in the fall and harvested in late spring, while castor is planted in the spring and harvested in late fall. Also, due to disparate requirements for water, temperature, and other climatic conditions, the crops will probably be grown in different parts of the country. Multiple production regions would provide a more reliable, domestic supply of hydroxy fatty acids. This in turn could encourage further research and new product development, thus opening additional markets for both crops.

Figure 2. U.S. Imports of Castor Oil, 1960-90.



Source: (19).

• • Production • •

In the late 1950s, ARS began a research program to develop new crops for the production of industrial oils, fibers, gums, natural rubber, and other chemical feedstocks. Over a 20-year period, ARS's National Center for Agricultural Utilization Research (NCAUR) in Peoria, Illinois, evaluated about 8,000 plant species for their potential as future crops [20].

During the 1960s, NCAUR's plant screening program identified the seed oils of various lesquerella species as a source of hydroxy fatty acids. Germplasm was collected from 25 lesquerella species, 14 from the arid Southwest. Seeds were analyzed for oil and hydroxy fatty acid content, which ranged from 11 to 39 percent and 50 to 75 percent, respectively [3, 4].

In the mid-1980s, researchers at ARS's U.S. Water Conservation Laboratory (USWCL) in Phoenix, Arizona, became interested in lesquerella because of its potential as a crop for the arid Southwest.

Lesquerella is only 6 years "out of the wild." Research has focused on plant selection, planting methods, irrigation, and harvesting. Remarkable agronomic progress has occurred in moving it toward commercialization, despite an annual commitment to the crop of less than one-half scientist year. (A scientist year is the time of one scientist working full time for a year).

Interest in lesquerella is growing. Recently, USWCL scientists have provided small quantities of seed to researchers in Alabama, Arkansas, California, Colorado, Georgia, Illinois, Iowa, Minnesota, Oregon, and Texas and to two private firms that operate worldwide.

Plant Characteristics

Plants in the genus *Lesquerella* belong to the *Brassicaceae* (mustard) family. Over 70 lesquerella species are known, all native to North America. The greatest concentration of species occurs in the southwestern United States and northern Mexico [1, 4, 21].

The genus is composed of annual, biennial, and perennial herbs. Plants generally have several to many stems. Flowers occur along the stems and are usually yellow. They develop into capsules containing numerous small, flat seeds. Native stands generally are found on well-drained, calcareous soils [1].

All species examined thus far have hydroxy fatty acids in the seed oil. Lesquerella species can be divided into three categories based on the major hydroxy fatty acid—lesquerolic, densipolic, or auricolic—in the seed oil. Usually, one acid predominates over the other two [16, 17].

In general, lesquerella species from the western United States produce oils containing high amounts of lesquerolic acid, while those from Alabama and Tennessee have densipolic acid as their major component. The one species with significant amounts of auricolic acid is native to Oklahoma and eastern Texas [16].

Plant Selection

In the mid-1980s, scientists at the USWCL assembled and evaluated the lesquerella germplasm that had been gathered in the 1960s. The collection consisted of 90 groups of plants from 23 species. *Lesquerella fendleri* was determined to have superior agronomic potential [3, 4, 22]. *L. fendleri* seed contains over 25 percent oil, by weight, and about 55 percent of that is lesquerolic acid [16].

Gentry and Barclay [2] first suggested *L. fendleri* as a candidate for domestication in 1962 after observing its growth and yield characteristics in wild populations. They were able to harvest several hundred pounds of seed with a standard combine from natural stands west of Pecos, Texas. *L. fendleri* seed is slightly smaller than alfalfa and most clover seeds. One million seeds weigh only 19.4 ounces.

Various line of lesquerella under evaluation in Arizona.

The natural range of *L. fendleri* is from southeastern Arizona to Texas and Oklahoma. This represents one of the widest distributions of any species in the genus [3]. It grows as a winter annual. Most of its growth and seed production occur between February and May. Wild stands have been found at elevations ranging from 2,000 to 6,000 feet in areas receiving from 10 to 16 inches of annual precipitation [2, 4].

In addition, considerable genetic variation has been observed within the species, which appears to be highly cross-pollinated [3]. These characteristics will provide plant breeders with opportunities to improve seed size, yield, oil content and composition, and other plant characteristics needed in a commercial oilseed crop.

Plant breeders may also be able to utilize genetic variation within the genus. For example, various other lesquerella species have seeds that contain as much as 39 percent oil and as high as 79 percent lesquerolic acid [16]. Seeds that are five times larger than those of *L. fendleri* have also been observed.

The encouraging results of the preliminary germplasm evaluation led a scientist at the USWCL to begin a breeding and selection program with *L. fendleri* in Arizona. The first yield experiment, utilizing an essentially unselected bulk population, produced an average yield of 1,060 pounds of seed per acre [3, 22]. (Throughout this report, seed yields from experimental plots are given on a per-acre-equivalent basis.)

Plant selection experiments started in 1985. Seed yields of the progenies of 39 single plant selections ranged from 785 to 1,550 pounds per acre, with an average of 1,190. This indicates a potential increase in yield of about 15 percent after only one generation of selection. Seeds of the 10 best lines were bulked for a second cycle of selection in 1986. The average yield of this new population was about 1,400 pounds per acre (table 1), 30 percent higher than the original bulk population [3, 22].

In 1988, USWCL researchers evaluated 330 progenies of single plant selections. Sixty of the best lines were harvested for yield. Six of these lines had average yields exceeding 1,800 pounds per acre. The seed from these six averaged 26 percent oil by weight, an equivalent of 476 pounds per acre. Lesquerolic acid comprised 52 percent of oil, equal to 248 pounds per acre.

Scientists have interbred the six best lines to produce a population from which a new cycle of selection was started. Yields of these new lines are presently being evaluated in a field experiment. Plant breeders are expecting yields of at least 2,000 pounds per acre from the best lines.

Lesquerella is performing well at an early stage of development. Significant further yield improvement can be anticipated [22]. Higher oil and hydroxy fatty acid percentages also are probable. For this to occur in the near future, however, additional resources are needed.

Table 1. Performance of *L. fendleri* Plant Selections, 1986 and 1988.

Item	Unit	Mean	Range
Ten best lines, 1986			
Plant population	Thousand per acre	195	69-365
Plant height	Inches	14.0	12.4-15.5
Plant dry weight	Pounds per acre	8,334	6,453-9,968
Seed yield	Pounds per acre	1,403	1,240-1,552
Seed weight	Ounces per million	21.9	19.1-25.6
Oil content	Percent, by weight	22.6	19.1-25.7
Oil yield	Pounds per acre	319	249-397
Lesquerolic acid content	Percent of oil	53.3	52.0-54.6
Lesquerolic acid yield	Pounds per acre	170	133-212
Six best lines, 1988			
Plant population	Thousand per acre	372	217-631
Plant height	Inches	16.3	13.6-21.6
Plant dry weight	Pounds per acre	11,480	8,702-17,210
Seed yield	Pounds per acre	1,822	1,610-2,329
Seed weight	Ounces per million	19.7	18.1-21.9
Oil content	Percent, by weight	26.1	22.6-28.8
Oil yield	Pounds per acre	476	376-595
Lesquerolic acid content	Percent of oil	52.3	51.1-53.4
Lesquerolic acid yield	Pounds per acre	248	201-312

Crop Production

In addition to their plant-selection work, USWCL scientists have initiated agronomic research to develop cultural and management practices for lesquerella production in Arizona [3]. Preliminary results indicate that lesquerella can be produced in a cropping system very similar to that of winter wheat or other small grains [4]. In contrast to some new crops, researchers are encouraged that no new equipment should be required to plant, produce, or harvest the crop.

L. fendleri appears to have an advantage over many other lesquerella species because it has minimal seed dormancy and germinates rapidly under favorable conditions [23]. Rapid seed increase is possible for commercial production, since the seed multiplication rate is more than 500 to 1. Because of the small size of *L. fendleri* seed, care must be taken to stop leakage in production and handling equipment, such as planter hoppers, combine augers, truck beds, and storage facilities.

In central Arizona, planting about October 1 appears to be optimal. Germination and seedling emergence occur in 7 to 10 days with adequate soil moisture and temperature. Seedling growth is relatively slow from November through early January. Indeterminate flowering begins in late February, with full bloom occurring during late March. Flowering may continue well into May, depending upon temperature, adequate soil moisture, and the amount of seed set. Seeds mature and plants dry during May. Harvest can occur in late May or in June. Seed moisture at harvest is low, so seed drying normally is not needed.

Lesquerella plots in an early stage of growth.

Planting lesquerella on raised beds using a Brillion seeder.

Preliminary research suggests that lesquerella in Arizona needs about 25 inches of water.

Planting. Various methods have been tested for planting lesquerella seed: row planting on 40-inch raised beds, broadcasting, and drilling with a precision seeder. So far, the most effective method has been drilling—on either raised beds or level fields. A Brillion seeder, a type of machine familiar to Arizona farmers growing alfalfa and other small-seeded crops, has been used successfully.

Initial research indicates that optimum populations are 400,000 to 500,000 plants per acre. Such populations can be achieved with 5 to 6 pounds of seed per acre, although actual populations will vary depending on seed germination and seedling survival. To further evaluate plant populations and planting methods, a field experiment was planted in October 1990 with a Brillion seeder using seeding rates of 4, 6, and 8 pounds per acre on level ground and raised beds.

Water Requirements. Although native stands of *L. fendleri* grow in arid conditions, commercial yields in Arizona will require irrigation. Low water availability not only reduces yield, but also decreases oil content of the seeds and the percentage of lesquerolic acid in the oil.

Researchers have conducted experiments to obtain data on lesquerella's water requirements. Preliminary results suggest that about 25 inches of water are needed during the growing season for good yields (table 2). This is essentially the same as the 26 inches required by most small grains grown as winter crops in Arizona. Cotton, on the other hand, needs about 42 inches of water per crop, and farmers often apply up to 60 inches.

Table 2. Mean Yields of *L. fendleri* With Different Irrigation Rates at Maricopa, Arizona, 1988.[1]

Item	Unit	Amount of water (in inches) used by the crop[2]					
		15.7		21.6		24.6	
Irrigations[3]	Number	3		4		6	
Plant							
Population	Thousand per acre	424	a[4]	469	a	582	a
Height	Inches	14.8	a	15.8	a	16.7	a
Dry weight	Pounds per acre	4,778	a	6,351	b	8,861	c
Seed							
Yield	Pounds per acre	589	a	946	b	1,264	c
Weight	Ounces per million	17.1	a	17.2	a	18.1	a
Seed oil							
Content	Percent, by weight	23.3	a	26.5	b	27.5	c
Yield	Pounds per acre	137	a	251	b	348	c
Lesquerolic acid							
Content	Percent of oil	49.8	a	52.2	b	54.3	b
Yield	Pounds per acre	68	a	131	b	189	c

[1]The *L. fendleri* used in this experiment was from an essentially unselected bulk population.

[2]Water depletion measured to a depth of 60 inches.

[3]Each irrigation application was about 4 inches.

[4]Means with different letters in a row are significantly different statistically at the 99 percent probability level.

Since fall rains during the planting season are unpredictable in Arizona, supplemental irrigation is particularly important for good germination and plant establishment. Researchers are studying various pre-emergence irrigation techniques. Flooding the field prior to planting is one method that has been successful, except for soils that are particularly susceptible to crusting. Poor stands may result under such conditions.

Researchers have also studied sprinklers as a method of supplying pre-emergence moisture. Water applied by sprinklers resulted in rapid germination and uniform stands. However, this type of irrigation is probably too expensive to be economically feasible for large-scale production in Arizona. Excellent plant stands were achieved using furrow irrigation and 40-inch raised beds in 1990 on a simulated commercial planting of 20 acres.

Current experiments focus on the timing of water applications and the combined effects of irrigation and nitrogen fertilizer. These factors may impact seed production, oil content and composition, and irrigation efficiency. Water use will continue to be an important issue for agriculture in the western United States, as various sectors of society bid for the scarce resource.

Fertilizer and Pest Control. In 1989, researchers began looking at fertilizer requirements and weed control. Preliminary results suggest that lesquerella yields can be increased by relatively small amounts of nitrogen applied during flowering and seed set.

Herbicides or cultural practices, such as the heavy seeding rates used on the left side of this field, are necessary to control weeds in lesquerella.

No conclusions can yet be drawn from the weed control experiments. In central Arizona, seedling growth is relatively slow between November and January. The plant canopy should provide full soil cover by early March under normal conditions. However, broad leaf weeds and grasses may be a problem before adequate plant cover is attained. Annual weeds also may be a problem shortly before harvest. Therefore, weed control—using cultural, chemical, and biological means—probably will be necessary. However, no herbicides currently are approved for use on lesquerella.

No detrimental insects or diseases have been observed on lesquerella. However, as with most crops, these problems usually occur with large-scale production and they should be dealt with as they arise.

Harvest. At maturity, *L. fendleri* is about 14 to 16 inches high. However, researchers are confident that taller plants can be developed through selection and breeding. During 1989, one plant line had an average height of 20 inches. Future varieties that are taller and remain erect will make mechanical harvesting easier and more efficient. A combine could operate at faster speeds, the header would not have to cut as near the ground, and a higher percentage of seed could be harvested.

Mature lesquerella plants are 14 to 16 inches tall.

Scientists have conducted experiments to test the feasibility of using conventional harvesting equipment. Results indicate that lesquerella seed can be harvested successfully with a standard combine equipped with sieve screens designed for small seeds.

In June 1988, over 1,000 pounds of seed were harvested by combine from experimental plots. Mean yields were over 980 pounds per acre, the equivalent of 16.3 bushels per acre. (A bushel of *L. fendleri* weighs about 60 pounds.) This represents 83 percent of yield obtained by hand-harvesting samples within the plots before mechanical harvest.

Lesquerella can be harvested with a small grain combine.

Besides the work conducted on small research plots, some lesquerella has been evaluated on a larger scale. In 1989, 5 acres of *L. fendleri* were used to test breeding material and for an irrigation experiment. In the fall of 1990, USDA cooperated with two private firms and the University of Arizona to plant 20 acres of lesquerella at Maricopa, Arizona. Harvesting efficiency tests were conducted on this acreage. In addition, one firm planted a total of about 10 acres at another location in Arizona. These plantings produced enough seed for researchers to conduct much needed product testing with the oil and meal.

Twenty-acre field of lesquerella at University of Arizona Experiment Station at Maricopa.

Like other oilseeds, lesquerella seed is crushed to produce oil and meal. The hydroxy fatty acids in the oil are the primary products of interest. However, lesquerella oil also contains other fatty acids, such as oleic, linoleic, and linolenic. The meal contains 30 to 35 percent protein, which makes it a good candidate for use as a protein supplement in cattle feed.

Some laboratory and pilot-scale experiments have evaluated methods to extract the oil and refine it, as well as inactivate an enzyme in the meal that produces unpalatable and antinutritional compounds.

Oil Extraction

Four primary methods exist to remove oil from oilseeds: expellers, prepress-solvent extraction, full solvent extraction, and extrusion followed by full solvent extraction. Hexane is the usual solvent. Using laboratory or pilot-scale equipment, researchers have tested all four processes with lesquerella seed.

Expellers (screw presses) mechanically crush oilseeds; no solvent is used to extract the oil. Expellers are popular in developing countries because of their mechanical simplicity. However, this process often leaves 3.5 to 10 percent oil in the meal [24]. Because other methods extract a higher percentage of oil, few of these type of oilseed mills remain in operation in the United States.

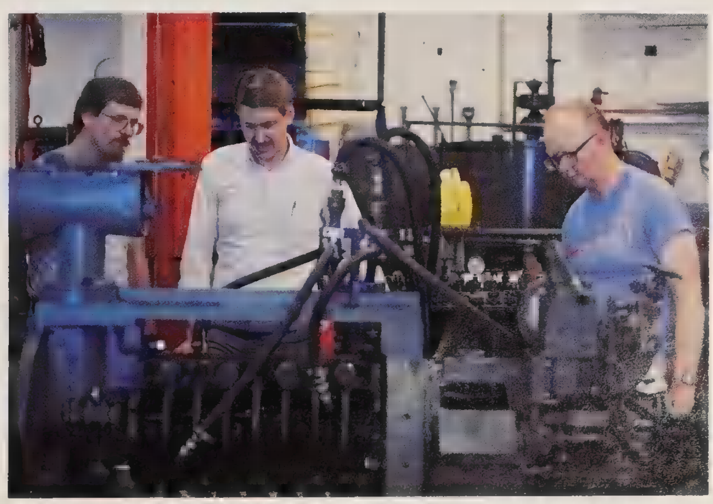
However, oil recovered from expellers tends to be of high quality. As a result, the cosmetic industry prefers press oils. In 1990, Jojoba Growers & Processors, Inc., successfully crushed about a ton of lesquerella seed with an expeller. The refined oil was provided to cosmetic firms for product testing.

When expellers are used for prepressing prior to solvent extraction, the goal is to extract at least half the oil. The resulting press cake moves on to a solvent extractor. For the solvent to work properly, the cake should be porous for intimate solvent contact, and maintain its structure and not crumble for good solvent flow. The solvent that does not drain out of the cake is removed in a desolventizer-toaster (DT) unit.

In 1989, USDA and the French Oil Mill Machinery Company of Piqua, Ohio, conducted pilot processing tests on lesquerella seed using both prepress-solvent extraction and full solvent extraction preceded by flaking. Commercial pilot-scale equipment was used. Results show that prepress-solvent extraction can successfully remove the oil from lesquerella seed [25].

Full solvent extraction typically is used for oilseeds with an oil content of less than 25 percent, mostly soybeans [24]. To prepare oilseeds for full solvent extraction, they are generally flaked to crush the seed coat and increase the surface area that comes

Processing lesquerella seed yields a valuable oil (shown) plus a meal.



Pilot expeller processing lesquerella seed at the French Oil Mill Machinery Company, Piqua, Ohio.

Extruded lesquerella collets prior to solvent extraction and a jar of oil.

in contact with the solvent. In the laboratory, researchers achieved satisfactory results with solvent extraction of lesquerella flakes [26]. However, in the pilot tests carried out at the French Oil Mill Machinery Company, inferior and fragile flakes resulted in unsatisfactory percolation rates [25].

Extrusion is the latest development in the oilseed industry for improving the efficiency of full solvent extraction. Extruders pressurize seed into a paste-like mixture. Upon release, the material rapidly expands and drys. The resulting pellets, called collets, are very porous. The collets increase solvent contact and reduce the amount of fine particles that impede solvent flow. In pilot-scale experiments conducted by Texas A&M University and ARS, extrusion followed by solvent extraction worked very well with flaked lesquerella seed. The seed produced excellent collets [27].

Oil Processing

Following extraction, oils are usually subject to further processing, such as degumming and bleaching. For many applications, such processing would be needed for lesquerella oil.

The method used for extracting the oil could influence the amount of processing. Oil recovered from a prepress operation is filtered to eliminate fine solids. The solution of oil and hexane from solvent extraction is filtered and then the hexane is evaporated off. Manufacturers often store and process press and solvent oils separately. They can behave differently in refining and bleaching, vary in quality, and be used in different applications.

In some instances, lesquerella oil may require traditional degumming, alkali refining, and bleaching. Degumming removes phosphatides, waxes, and other impurities from the crude oil. Conventional alkali refining neutralizes and removes free fatty acids from degummed oil. Bleaching eliminates pigments found in the crude oil.

Crude lesquerella oil has a distinct reddish color [27]. In the laboratory, researchers have removed a significant amount of this color by using charcoal and bleaching clays. So far, the refined oil is still darker than refined castor oil.

The amount of degumming, refining, and bleaching lesquerella oil will undergo will be determined by its intended uses. For example, if fatty acids are the desired products, the crude oil can probably be split directly without any refining. (Vegetable oils are triglycerides, three fatty acids attached to a glycerol "backbone." Splitting separates the fatty acids from the glycerol.)

Lesquerella Meal

Lesquerella seed contains glucosinolates, as do the seeds from all native plants of the *Brassicaceae* (mustard) family, such as industrial rapeseed, crambe, broccoli, turnips, and cabbage. (Edible rapeseed varieties have been selected and bred to be low in erucic acid and glucosinolates.)

Lesquerella oil has a distinct reddish color; further bleaching studies are needed for some applications.

Glucosinolates, sulfur-containing glucose compounds, usually remain in the meal after the seed is crushed. Small amounts may appear in the oil and can interfere with some chemical reactions, such as hydrogenation, during manufacturing [26, 27].

The meal also contains an enzyme—thioglucosidase—that converts glucosinolates into isothiocyanates and thiooxazolidones. These compounds may adversely affect thyroid glands of swine and poultry [28, 29]. Ruminants, such as cattle, exhibit much greater tolerance [30].

For cattle feed, the best way to maintain the quality of the meal is to inactivate the enzyme during processing, thereby preventing the breakdown of the glucosinolates. Research has demonstrated that this can be done for lesquerella and other glucosinolate-containing meals, such as industrial rapeseed and crambe.

Experiments have shown that cooking the seed before crushing it is one way to inactivate the enzyme. The seed is placed in "cookers" and water is added to bring the moisture up to 10-15 percent. Then, temperatures are raised to 200°F and maintained for up to 45 minutes [25]. The time may vary, depending on moisture and temperature. Cookers are used in crushing mills to condition many oilseeds for oil extraction. This process is used commercially to inactive the enzyme in industrial rapeseed.

Researchers suspect that the thioglucosidase enzyme can be inactivated in extruders that are designed to prepare seed for solvent extraction. Pilot-scale tests at Texas A&M University confirmed this theory. The heat generated in the extruder, in conjunction with moisture levels of about 10 percent, was sufficient to inactivate the enzyme [27].

If cooking or extrusion does not completely inactive the enzyme, the desolventizer-toaster could be used to finish the job. In test runs at commercial oilseed mills during the 1970s, DT units were used to inactivate the enzyme in crambe meal [31].

A simple procedure has been developed to determine if the enzyme has been inactivated, either in the seed or in the meal. The material is ground into a powder and mixed thoroughly with distilled water. The mixture is then tested with glucose tape. If the tape—used by diabetics to check for glucose in their urine—does not turn green, the enzyme has been inactivated [26, 27].

Based upon experiments thus far, extrusion followed by full solvent extraction appears to be the method of choice for extracting oil from lesquerella seed. Flaked lesquerella seed forms good collets, a high percentage of the oil is recovered by solvent extraction, and the process inactivates the thioglucosidase enzyme. Individuals familiar with extruders in commercial oil mills report that the equipment pays for itself in less than a year.

Chemists have conducted only minimal research on uses of lesquerella oil. However, it should be a good raw material for use in manufacturing many industrial products. Lesquerella derivatives might substitute directly for ricinoleic acid and other castor oil products, the only commercially available sources of hydroxy fatty acids. Lesquerella oil and its derivatives may even improve product quality or performance. Moreover, they might be used for totally new industrial applications [17, 32, 33].

Some preliminary analyses have compared lesquerella and castor oils [26]. However, further research is needed to validate the functionality of lesquerella oil derivatives, not only in the laboratory, but also in commercial applications.

Alka Chaudhry of ARS-NCAUR formulating lubricating grease from lesquerolic acid.

The following discussion highlights some potential uses for lesquerella fatty acids, oil, and meal. The possible applications mentioned here are based on limited testing and known characteristics and properties of oleochemicals. Researchers have focused on the oil from *L. fendleri* because the species appears to have the best agronomic and chemical potential.

Hydroxy Fatty Acids

Initially, lesquerella oil will not substitute directly for castor oil in uses where the hydroxy acid content is a critical factor. Lesquerella oil only contains about 55 percent hydroxy fatty acids versus nearly 90 percent for castor oil. To obtain high concentrations of hydroxy acids from lesquerella oil, splitting would be necessary. The hydroxy fatty acids then could be separated from the glycerol and other fatty acids.

Ricinoleic acid and lesquerolic acid are similar. Each has a double bond and a hydroxyl group the same distance from the methyl (CH_3) end of the fatty acid molecule. They differ, however, in that lesquerolic acid has two more carbon atoms in the carboxyl (CO_2H) end of its structure. (See figure 1 and previous discussion on hydroxy fatty acids.) This chemical difference means that both common and different products may be derived from the two hydroxy acids. Where higher molecular weights are important for the chemical properties of the products, lesquerolic acid could be superior.

Ricinoleic acid is used in cutting oils, industrial lubricants, transparent bar soaps, heavy duty detergents, inks, coatings, plastics, and textile processing agents [34]. Like ricinoleic acid, lesquerolic acid can be made into several different products using various chemical processes. However, until lesquerella oil has a higher hydroxy acid content—above 80 percent, for example—lesquerella fatty acids will be at a disadvantage to castor acids in some applications.

One of the most obvious derivatives obtainable from lesquerolic acid is the saturated hydroxy fatty acid 14-hydroxy-eicosanoic acid. This can be produced by hydrogenation of lesquerolic acid, where hydrogen is added to the double bond in the carbon chain. This 20-carbon saturated acid is a homolog of 12-hydroxystearic acid obtained from castor oil. (Homologous organic chemicals are similar compounds, differing only in the number of CH_2 groups they contain.)

Lubricating grease, beverage can coatings, soap, and lipstick are some products that potentially can be made from lesquerella oil. The items are representative of classes of products that use castor oil or its derivatives; the items shown may or may not contain castor oil.

Lipstick formulated from lesquerella oil colors very well and maintains its form and consistency.

Hydrogenated lesquerolic acid may be useful in products similar to those now containing hydrogenated castor fatty acids. 12-hydroxy-stearic acid is a major component in multipurpose lubricating greases; cosmetics and toiletries; polishes; inks; and coatings for appliances, machinery, and automobiles [34].

Fatty acids and their derivatives can be reacted with metals—such as lithium, aluminum, calcium, lead, and zinc—to form metal soaps. These soaps are not water soluble and can be used as thickeners in lubricating greases. Soaps obtained from lesquerolic acid have higher molecular weights than those from ricinoleic acid. Therefore, greases produced from these materials may have improved properties, including better lubrication and thermal stability.

To test these properties, NCAUR research chemists conducted preliminary evaluations of grease formulations using a derivative of lesquerolic acid [35]. Results were encouraging but more research is required on complete grease formulations before in-depth comparisons can be made with castor-based greases.

Lesquerolic acid can be cleaved by a combination of heat and alkali to produce industrially useful materials. Lesquerolic acid in the presence of sodium hydroxide above 480°F produces

dodecanedioic acid (a C_{12} dibasic acid) and 2-octanol [36, 37]. Ricinoleic acid, under the same conditions, yields sebacic acid (a C_{10} dibasic acid) and 2-octanol [38, 39, 40].

Dodecanedioic acid has many commercial uses. For example, it is used as textile sizing and as the major ingredient in nylon-1212, nylon-612, and other molded plastics. Dodecanedioic acid is now manufactured from petrochemicals through a complex synthesis starting with butadiene. However, market opportunities may exist for lesquerolic acid because of consumers' environmental concerns and desire for natural products. 2-octanol is used in the manufacture of perfumes, soaps, and antifoaming agents.

Another important reaction of ricinoleic acid is its thermal fragmentation to heptanal (C_7) and undecenoic acid (C_{11}). The latter is reacted with hydrogen bromide and ammonia to form an amine acid monomer, the basic building block for producing nylon-11. A homologous C_{13} amine acid monomer can be made from lesquerolic acid for the manufacture of nylon-13.

The automotive industry increasingly is using these types of long-chain nylons in thermoplastic items [41]. In addition to the typical properties of toughness, strength, and chemical resistance, long-chain nylons are lightweight. Such materials can be used to make gears, tubing, fasteners, and other automotive parts.

Hydroxyamide waxes result from the reaction of amines with ricinoleic acid. These waxes are used as sealants, plastizers, mold lubricants and release agents in plastic extrusion and molding, antistatic agents for textile processing, pigment dispersants for plastics and coatings, antistatic and antiblock agents for inks and adhesives, and a binder/lubricant for powdered metals [34]. Similar amide waxes from lesquerolic acid probably could be used in these applications, and the higher molecular weight may be beneficial.

Other Fatty Acids

The other fatty acids in lesquerella oil also occur in other vegetable oils and animals fats (table 3). These fatty acids—oleic, linoleic, and linolenic—accounted for 29 to 36 percent of the *L. fendleri* oils analyzed by the NCAUR (table 4).

Table 3. Major Fatty Acids of Some Common Oils and Fats.

Oil or fat	Fatty acid			
	Oleic	Linoleic	Linolenic	Other
	Percent[1]			
Castor oil	2.7	4.4	0.6	89.1 ricinoleic
Cottonseed oil	19	50	—	22 palmitic
Linseed oil	25	14	42	
Industrial rapeseed oil	26	16	6	52 erucic
Safflower oil	11.4	78.7	—	6.7 palmitic
Soybean oil	27.2	50.3	6.3	6.5 palmitic 4.2 stearic
Sunflower oil	29	56	—	5 palmitic
Tall oil fatty acids	46.4	36.3	—	
Lard	41.4	6.7	—	26.7 palmitic 20.1 stearic
Tallow	38	1.8	—	31 palmitic 22 stearic

— = None present.

[1]Average values.

Source: [42, 43].

Table 4. Fatty Acid Composition of *L. fendleri* Oils.

Fatty acid	Chemical acronym[1]	Percent[2]
Palmitic acid	16:0	0.8-1.1
Stearic acid	18:0	1.4-1.8
Oleic acids[3]	18:1	14.0-17.9
Linoleic acid	18:2	5.2-6.5
Linolenic acid	18:3	9.7-11.2
Gadoleic acid	20:1	0.6-0.8
Epoxy linoleic acid	18:2-epoxy	0.5-1.1
Hydroxy palmitoleic acid	16:1-OH	0-0.1
Ricinoleic acid	18:1-OH	0.3-0.4
Densipolic acid	18:2-OH	0-0.1
Lesquerolic acid	20:1-OH	54.7-59.7
Auricolic acid	20:2-OH	3.0-4.8

[1]Chain length, number of double bonds, and functional groups, if any.

[2]Percentage range of fatty acid contained in the four lines of *L. fendleri* tested.

[3]Includes oleic acid and an isomer with the double bond in the 11 position.

Source: [16].

Of those fats and oils containing oleic, linoleic, and linolenic acids, cottonseed, safflower, and sunflower oils and lard are primarily used for edible purposes. Margarines and cooking oils are examples. Linseed and tall oils are exclusively used in industrial applications. Although most soybean oil is used in edible products, some moves into manufacturing channels. In fact, 30 percent of the fats and oils consumed in the United States during 1979/80-1988/89 were for industrial uses. Fatty acids and animal feeds accounted for two-thirds of this amount (table 5). (For further information on the industrial uses of fats and oils, see appendix B.)

Tall oil, inedible tallow, coconut oil, and soybean oil were the major sources of fatty acids (table 6). Coconut oil has high concentrations of lauric acid, which is used in soaps and surfactants [44]. Tall oil, tallow, and soybean oil contain many of the other fatty acids that are in lesquerella oil.

Table 5. Inedible Uses of Fats and Oils, by Product Class.

Product class	Annual average 1979/80-1988/89[1]	Percent of total
	Million pounds	
Soap	801.0	15
Paint or varnish	172.9	3
Feed	1,586.5	29
Resins and plastics	168.9	3
Lubricants and similar oils	111.3	2
Fatty acids	2,046.6	37
Other inedible uses	573.6	10

[1]Crop years, which run from October 1 to September 30.

Source: [10].

Table 6. Amounts of Fats and Oils Used for Fatty Acids, 1979/80-1988/89.

Crop year[1]	Coconut oil	Soybean oil	Tall oil	Inedible tallow	All fats and oils
			Million pounds		
1979/80	106.5	21.2	1,208.2	814.6	2,206.2
1980/81	102.1	22.8	1,205.9	813.3	2,195.0
1981/82	98.8	21.5	1,096.2	736.9	2,003.2
1982/83	100.4	15.9	1,041.5	618.5	1,843.2
1983/84	102.8	20.8	1,095.8	700.2	1,993.5
1984/85	63.9	29.1	994.2	767.3	1,931.5
1985/86	59.7	31.5	1,055.2	733.4	1,968.9
1986/87	95.7	d	1,152.6	693.6	d
1987/88	131.4	d	1,181.1	712.6	2,203.8
1988/89	121.9	d	1,157.3	680.0	2,074.1

d = Data withheld to avoid disclosing figures for individual companies.

[1]October 1 to September 30.

Source: [10].

Tall oil is a byproduct of pulp manufacture in kraft paper mills. Crude tall oil is a mixture of fatty acids, rosin acids, and unsaponifiables [42]. Fractional distillation is used to separate the fatty acids from the other components [45]. Tall oil fatty acids are used in intermediate chemicals, such as dimer acids and epoxidized tall oil fatty acid esters; protective coatings; soaps and detergents; and ore flotation [42]. The declining use of pine trees for the manufacture of paper could increase the demand for other sources of oleic and linoleic acids [44].

Tallow can be separated into solid and liquid segments. The liquid component, known as red oil, is oleic acid. The palmitic and stearic acids remain in the solid portion [46].

Soybean fatty acids are used widely as animal feed ingredients and chemical raw materials. The feed industry incorporates them into animal, poultry, and pet foods, where they serve as an energy source. Oleic, linoleic, and linolenic acids are also used in industrial cleaners. For example, they are used in medium-grade soaps and detergents for a wide variety of laundry and industrial cleaning operations. Sonntag states that a market in excess of 200 million pounds exists for these types of materials, with a value of 15 to 20 cents per pound [47].

Direct use of oleic and linoleic acids or their derivatives in low cost industrial applications is another possibility. These uses include alkyd resins, dimer acids, coatings, surfactants, and possibly polymers such as nylon-9 and nylon-99. If hydrogenated, these fatty acids yield product with 90 percent stearic acid that can be used in a wide array of applications [47].

These acids can also be esterified and then epoxidized to produce epoxy esters that may have applications as low temperature plasticizers and stabilizers for polyvinyl-chloride resins [48]. In contrast to some uses, the epoxidized esters could have a relatively high value, in the range of 50 to 75 cents per pound.

Researchers and industry are faced with the challenge of economically separating lesquerolic acid from the other fatty acids. Income from these other fatty acids will help offset separation costs. The value of the glycerol often is sufficient to cover the cost of splitting.

Oil

Although hydroxy fatty acids are expected to be the primary products from lesquerella, direct uses of the oil may be developed. Castor oil itself is used in many applications. For example, dehydrated castor oil is an excellent drying oil and is used by the coatings industry. (Dehydration removes the hydroxyl groups.) Dehydrated lesquerella oil should have similar properties, since virtually all the non-hydroxy acids are mono or polyunsaturated.

Reacting lesquerella oil with sulfuric acid yields a sulfonated oil that should have properties analogous to sulfonated castor oil, commonly called Turkey red oil. The textile industry is a major user of Turkey red oil for fiber wetting [39, 40].

Blowing air through castor oil oxidizes it. The oxidized oil, sometimes called blown castor oil, is used as a nonvolatile, nonmigrating plasticizer for polyamides, resins, and rubber. ARS chemists believe that analogous products from lesquerella oil should have comparable or superior properties.

Plastics made with interpenetrating polymer networks (the carbon chains are interconnected with chemical bonds) have been produced from lesquerella oil [33]. Because of the higher molecular weight of lesquerella oil, the plastics may have greater flexibility and resistance to moisture. Lesquerella oil should produce very good elastomers and excellent rubber-toughened plastics.

Waxes made from lesquerella oil have not yet been prepared, but such materials may complement hydroxy waxes from castor oil. Castor waxes are used in metal drawing lubricants, processing aids for rubber and plastics, strippable coatings, pencils and crayons, cosmetics, antiperspirant sticks, and electrical-potting compounds [34].

Meal

Lesquerella meal is a good candidate for use as a protein supplement in livestock rations, primarily for beef cattle. It contains 30 to 35 percent protein. In comparison, rapeseed meal has 36 to 38 percent protein and soybean meal, 44 to 50 percent [49].

Lesquerella meal has a good amino acid balance, and one that compares favorably with soybean meal (table 7). Scientists have analyzed the meal from 14 lesquerella species. *L. fendleri* meal was one of the best in terms of its amino acid content. The levels for 17 out of the 18 amino acids tested were higher than the average for all species. The amount of lysine, an essential amino acid frequently deficient in seed proteins, was similar to the quantity found in soybean meal.

Lesquerella meal contains 30 to 35 percent protein and has a good amino acid balance.

In the southwestern United States, more protein meal is fed to livestock than is produced locally. Therefore, meal is purchased from other parts of the country. *L. fendleri* meal could provide the region with an additional source of protein.

Initial feeding trials with lesquerella meal currently are underway. Speculation on potential uses is possible based on its similarities to industrial rapeseed and crambe meals. Glucosinolate levels are lower in lesquerella meal than in industrial rapeseed or crambe meal.

Research in Canada indicates that glucosinolate-containing rapeseed meal is suitable as the sole protein supplement in feed rations for calves, growing heifers and bulls, lactating dairy cows, and beef cattle [49]. However, the meal should be gradually introduced into the rations because palatability may be a problem [52]. Crambe meal can also be used in beef cattle rations [30, 31].

Lesquerella meal entering interstate commerce would require approval by the Food and Drug Administration (FDA) as a feed ingredient. However, the necessary tests are both costly and lengthy. FDA requires feeding trials comparing lesquerella meal with a standard ration. This generally entails feeding two animal species in two different replications. The process could take up to 4 years using approved procedures.

FDA has approved industrial rapeseed and crambe meals for use in finishing rations for beef cattle. Mechanically extracted rapeseed meal must have at least 32 percent protein and no more than 12 percent crude fiber [53]. Solvent-extracted crambe meal can constitute not more than 4.2 percent of the ration, by weight [30].

Table 7. Amino Acid Composition of Lesquerella and Soybean Meals.[1]

Amino acid	14 lesquerella species[2]		*L. fendleri*[3]	Soybean[3]
	Mean	Range		
	Grams per 16 grams nitrogen			
Alanine	3.92	3.34-4.50	4.50	4.29
Arginine	7.07	5.84-8.05	7.86	7.26
Aspartic acid	6.51	5.82-7.41	7.23	11.78
Cystine	2.11	1.78-2.37	1.78	0.93
Glutamic acid	12.85	11.14-14.08	13.70	18.62
Glycine	4.94	4.26-5.94	5.94	4.30
Histidine	2.22	1.98-2.53	2.53	2.54
Isoleucine	3.42	3.10-3.68	3.55	4.58
Leucine	5.49	4.83-6.02	5.81	7.74
Lysine	6.22	5.30-7.04	6.64	6.43
Methionine	1.31	1.15-1.50	1.34	1.14
Phenylalanine	3.42	2.91-3.82	3.82	5.01
Proline	6.43	5.39-7.81	6.67	5.10
Serine	3.86	1.87-4.78	4.64	5.46
Threonine	3.97	3.70-4.45	4.45	3.94
Tyrosine	2.72	2.43-3.02	2.98	3.74
Valine	4.66	4.16-5.09	4.78	4.58

[1]Soybean meal included for comparison.

[2]Includes *L. fendleri*.

[3]Mean values.

Sources: [50, 51].

The demand by manufacturers for production inputs, like lesquerella's fatty acids, is derived from the demand by consumers for the products containing those inputs. For example, the demand for wheat by flour millers is based on consumers' demand for bread and other wheat-based foods. Likewise, the demand for Turkey red oil, a castor oil derivative, by the textile industry is rooted in consumers' demand for clothing and other fabric items.

Consumer demand will also determine the derived demand for lesquerella raw materials. Moving back through the marketing channel toward the farmer, the demand for lesquerella seed will be derived from the demand for the oil and meal. However, farmers will only be willing to grow the crop if revenue exceeds costs.

Although lesquerella is only in the beginning stages of development, rudimentary estimates of the value of the seed—based on prices of similar oils and meals—and production costs can be proposed. The following estimates are based on information about the oil and meal of *L. fendleri*.

Estimated Value

The value of lesquerella seed can be estimated based on the value of the oil and meal in the seed, less processing costs. This relationship can be represented by the following equation:

$$V_S = [V_O(\%O) + V_M(1\text{-}\%O)] - PC_S$$

where:

V_S = value of lesquerella seed,
V_O = value of lesquerella oil,
$\%O$ = oil content of the seed,
V_M = value of lesquerella meal, and
PC_S = processing costs for the seed.

The value of the meal can be estimated based on prices for other oilseed meals. However, the value of the oil is based on its fatty acid content. The equation representing this relationship would be:

$$V_O = [V_{LA}(\%LA) + V_{OFA}(1\text{-}\%LA)] - PC_O$$

where:

V_{LA} = value of the lesquerolic acid,
$\%LA$ = lesquerolic acid content of the oil,
V_{OFA} = value of the other fatty acids in lesquerella oil, and
PC_O = processing costs to split and separate the fatty acids.

In this analysis, it is assumed that 100 percent of the oil, meal, and fatty acids are recovered during processing. However, recovery rates in commercial oilseed facilities can vary depending on the extraction method used, the age of the equipment, and other factors.

The value of lesquerella oil was estimated using the following parameters:

V_{LA} = The average list price for ricinoleic acid, October 1990 to March 1991, which was 81 cents per pound [54]. During the period, prices ranged from 79.5 to 83 cents per pound.

$\%LA$ = Lesquerolic acid content, ranging from 55 to 70 percent. *L. fendleri* oil currently contains about 55 percent lesquerolic acid.

V_{OFA} = Two estimates were used for this variable:
(1) Average list price for soybean oil soapstocks (acidulated, 95 percent acid, tank cars, New York), October 1990 to March 1991. This was 14.5 cents per pound; prices ranged from 14 to 15 cents [54].
(2) Average list price for soybean oil acid (single distilled, tank cars), October 1990 to March 1991. This was 44.5 cents per pound; prices ranged from 44 to 45 cents [54].

The cost of processing the crude oil into fatty acids requires splitting the fatty acids from the glycerol and separating the hydroxy fatty acids from the other fatty acids. Revenue from selling the glycerol often covers the cost of splitting. Research has not yet been conducted on separating the hydroxy and other fatty acids. As a result, separation charges are unknown. Therefore, no attempt was made to include these costs in this analysis.

With a current lesquerolic acid content of 55 percent, the value of the oil is estimated to be 51 or 65 cents per pound, depending on how the other fatty acids are valued (table 8). If researchers are able to increase lesquerolic acid to 70 percent, the oil could be worth as much as 70 cents per pound.

Table 8. Estimated Value of Lesquerella Oil.

Lesquerolic acid content	With the other fatty acids valued at: 14.5 cents per pound	44.5 cents per pound
Percent	Cents per pound	
55	51	65
60	55	67
65	58	68
70	61	70

Using these values for the oil, the value of the seed can be estimated. The following parameters were used:

%O = Oil content of the seed, ranging from 25 to 35 percent. *L. fendleri* seed presently contains 25 percent oil.

V_M = The value of lesquerella meal is estimated to be about $120 per ton. This is comparable to the price of linseed meal [54], which has a similar amount of crude protein, contains antinutritional compounds, and is a commercial feed ingredient for ruminant animals in some parts of North America [49].

PC_s = Crushing costs were estimated at 20 cents per pound ($40 per ton). The oilseed industry in the United States presently has excess crushing capacity—more crushing facilities exist than are needed to process current oilseed production. Processing costs would be higher if this situation did not exist, possible $50 to $60 per ton. Transportation and storage costs were not included in the analysis. Specific production areas are unknown, as is the distance to mills that would be equipped to handle the small seed.

Given the current oil and hydroxy fatty acid content of *L. fendleri* seed, it may be worth about 15 cents per pound (table 9). This is just a rough estimate of the actual price; lesquerella seed may fetch more or less in the marketplace. With more oil and lesquerolic acid, the value may be as high as 23 cents per pound.

Table 9. Estimated Value of Lesquerella Seed.[1]

Oil content	Percent lesquerolic acid in the oil: 55	60	65	70
Percent	Cents per pound			
25	15.3	16.3	17.0	17.8
26	15.7	16.7	17.5	18.3
27	16.2	17.2	18.0	18.9
30	17.5	18.7	19.6	20.5
35	19.8	21.2	22.2	23.3

[1]With the other fatty acids valued at 14.5 cents per pound. See table 8.

In 1988, USWCL scientists reported experimental yields of about 1,800 pounds per acre for their six best lines of lesquerella and they expect yields of about 2,000 pounds from their latest plant selections. With those yields and seed valued at 15 cents per pound, lesquerella could be worth between $270 and $300 an acre.

Estimated Farm Costs

USWCL scientists suggest that production costs for lesquerella should be similar to those for irrigated durum wheat, which yields about 85 bushels per acre in Arizona [55]. Farm level budgets developed by the Arizona Cooperative Extension Service estimate the cash operating expenses for producing durum wheat in 1990 were about $237 per acre (table 10) [56].

Two changes were made in the durum wheat budget to reflect what scientists currently know about lesquerella production. First, lesquerella seeding rates are expected to be about 6 pounds per acre. The cost of high-quality planting seed was estimated to be 30 cents per pound. Thus, seed costs are calculated to be $2 per acre. Second, custom harvesting expenses were increased by 20 percent to account for the slower ground speeds needed for lesquerella. With these adjustments, lesquerella's preliminary cash operating expenses are estimated to be a little lower than those for durum wheat.

Two agricultural economists at the University of Arizona recently agreed to work with the CSRS Office of Agricultural Materials to develop more definitive cost estimates for lesquerella production. These figures will be based on technical coefficients developed by agronomists and agricultural engineers, as well as on information from existing crop budgets.

Table 10. Cash Operating Expenses for Durum Wheat and Lesquerella in Arizona, 1990.

Item	Budgeted amount	
	Durum wheat	Lesquerella
	Dollars per acre	
Paid labor	23.27	23.27
Tractor	7.96	7.96
Irrigation	13.43	13.43
Other	1.88	1.88
Seed	19.60	2.00
Fertilizer	57.07	57.07
Farm machinery	28.89	28.89
Diesel fuel	6.18	6.18
Gasoline	3.38	3.38
Repairs and maintenance	19.33	19.33
Irrigation	88.13	88.13
Electricity	70.87	70.87
Repairs and maintenance	17.26	17.26
Other	19.75	22.30
Custom harvesting	12.75	15.30
Operating interest	7.00	7.00
Total	237.34	222.29

• • PMC System and Delphi Survey • •

The task force used a production/marketing/consumption (PMC) system to examine the commercial potential of lesquerella. The group evaluated the technical, economic, and institutional aspects of crop production, product consumption, and marketing—including procurement, processing, and product distribution. An obstacle anywhere in the system can preclude successful commercialization.

Four major requisites must exist for successful commercialization of lesquerella:

- Farmers must be able to produce the crop reliably and profitably.
- Processors must be able to cost-effectively extract and separate products of interest.
- Products and markets must exist or be developed.
- Consumers must purchase products at prices that result in profits for each subsector.

A Delphi survey was used to confirm the task force's perceptions about lesquerella's level of development. The survey gleaned input from knowledgeable individuals. No insurmountable barriers to commercialization were identified by the task force or survey respondents.

PMC System

The PMC system is a theoretical framework that ties together all the diverse components needed to produce, process, and utilize a crop. It is an attempt to portray the complex interrelationships that move a crop and its products from production to consumption.

The PMC framework is composed of three subsystems—production, marketing, and consumption. The marketing subsystem is further subdivided into procurement, processing, and distribution phases [57].

Each component within the system—production financing or processing equipment, for example—is evaluated based on three criteria. Is it technically possible to perform the function? Is it economically feasible to do so? Is it institutionally permissible?

The concept of institutional permissibility may not be as obvious as the other two factors [58]. Depending on the component, it could reflect individual behavior, social attitudes, or governmental policy and regulations. For instance, some farmers may not be interested in growing new crops or they may feel restrained by what their neighbors will think. Processors face some of the same pressures or they may be excluded from marketing channels by other firms. Also, new crops must fit into the current regulatory environment, whether that means planting them on flex acreage (as is allowed by Federal commodity programs) or applying for building permits for a new processing plant.

The PMC methodology was developed in a 1981 study funded by the National Science Foundation and was used to evaluate six potential crops—crambe, guayule, grain amaranth, jojoba, kenaf, and pigeon pea [57].

Delphi Survey

A Delphi survey was administered in 1989 to gather information from knowledgeable individuals concerning opportunities and hindrances for commercializing lesquerella. (See appendix A for the list of respondents.)

The Delphi technique is directed toward the systematic solicitation of expert opinion [59]. It relies on an iterative process. Questions are given to knowledgeable individuals for response. The survey administrator summarizes their answers and then provides the same set of questions with summarized answers to the individuals. Their second responses reflect access to the summary information. This iterative process is continued until an acceptable consensus is achieved. The Delphi technique has been widely used for technological forecasting, particularly for corporate planning and military research and development [60].

When evaluating new crops, Delphi surveys have been administered based on the PMC framework. Questions were grouped according to the technical, economic, and institutional criteria. The number of iterations was limited. Two rounds were conducted for technical possibility and economic feasibility and one round for institutional permissibility [57].

The task force followed this procedure in its survey for lesquerella. Because of the limited number of rounds, the respondents did not reach a consensus on a few issues.

In the first round, respondents were asked to rate the technical possibility and economic feasibility of each question on a scale from 5 (no constraint) to 1 (completely constrained). In addition, they were encouraged to provide written comments, rationale, or judgments concerning a question.

Feedback from the first round consisted of average scores, degree of consensus, and summary statements. Individual responses were kept confidential and only summary data from the group were distributed. This information was mailed to respondents with the next round of questions.

In the second round for technical and economic factors, respondents agreed or disagreed with the summary statements for each question and could again provide comments or rationale. The round on institutional permissibility was administered at the same time. People responded to summary statements developed by the survey administrator based on the information gathered by the task force. (Appendix C, table C1, contains the survey questions and summary statements.)

Fifteen individuals responded to questions in all phases of the Delphi survey. They represent various areas of expertise from private firms, Federal agencies, and universities. The degree of familiarity with lesquerella varied considerably, as is common for any potential new crop.

Survey Results

Respondents to the survey indicated that hindrances to commercializing lesquerella do exist. This is not surprising, since minimal research and development has occurred at many of the PMC stages. Highlights of the results follow.

Production. Respondents perceived the production subsystem as less constrained than the marketing and consumption subsystems.

Although production of lesquerella is technically possible, respondents perceived the lack of input market information as a highly constraining factor (table 11). This is somewhat surprising, since most inputs other than seed appear to be similar to those for existing crops and market information is readily available. However, respondents may have been reacting to the current lack of information on lesquerella's input needs.

Respondents also rated as a major hinderance the technical prospects of lesquerella commercialization if a small amount of resources were allocated to the task. However, considerable disagreement occurred on this question. Some divergence of opinion also existed on how rapidly institutions could be developed, both technically and institutionally, to exchange production information. (See appendix C, table C2, for data on survey responses.) Respondents rated the technical aspects of the remaining production components as either moderately constraining or having no substantial constraints.

Respondents viewed three economic factors as highly constraining. First, land allocation may be a problem for lesquerella production. Second, it may be difficult for farmers growing lesquerella to obtain adequate financing for operating expenses. This frequently occurs when farmers become involved in new enterprises. Third, limited funding may constrain the ability of researchers to respond to critical production problems. Respondents rated another 10 components as moderately constraining.

Disagreement occurred on the economic feasibly and institutional permissibility of land allocation. Some thought the base acreage requirements of Federal commodity programs may limit the land devoted to lesquerella. (The survey was completed before passage of the 1990 Food, Agriculture, Conservation, and Trade Act, which allows some planting flexibility on base acreage.) The expense of developing market information for producers also generated some differences of opinion.

Table 11. Mean Rating of Respondents to Lesquerella Delphi Survey for PMC Production Subsystem.

Production component[2]	Mean rating[1]		
	Technically possible	Economically feasible	Institutionally permissible
Land allocation	4.18	2.82	4.00
Water allocation	4.00	3.44	4.11
Production financing	3.60	2.63	3.11
Pest control	3.53	3.50	3.11
Seed availability	3.15	3.93	3.56
Fertilizer availability	4.44	4.14	4.78
Input transportation and storage	4.44	4.40	4.33
Managerial ability	3.56	3.27	4.00
Production equipment	4.38	4.06	4.22
Energy availability	4.25	4.19	4.33
Input market information	2.88	3.53	3.22
Government services and regulation (production)	3.38	3.44	3.78
Production research	3.24	2.65	3.33
Information dissemination programs	3.65	3.53	3.78
Information exchange institutions	3.29	3.24	3.44
Farm labor needs	4.59	4.41	4.22
Market information for producers	3.13	3.19	4.33
Germplasm development	3.67	—	—
Commercialization prospects	2.93	—	—

— = Not applicable.

[1]Rating scheme: 1.00-1.99, completely constrained; 2.00-2.99, highly constrained; 3.00-3.99, moderately constrained; and 4.00-5.00, no substantial constraints.

[2]Corresponds to a Delphi survey question and accompanying summary statements. See appendix C, table C1.

No institutional factors were perceived as highly constraining for lesquerella production. However, respondents expressed concern about the lack of approved chemicals for insect and weed control. Respondents also identified governmental and societal reluctance to fund research for industrial products and new crops, such as lesquerella, as a moderately constraining factor.

Some disagreement occurred on whether institutions exist, or rapidly can be developed, to facilitate exchange of lesquerella-specific information. A few respondents also indicated that pest control may not be as prohibitive as some expect.

Marketing. In evaluating the technical possibility of marketing lesquerella, most respondents identified two items as highly constraining. Lack of a procurement network and a dependable supply of lesquerella seed were viewed as major impediments (table 12). Fourteen factors were perceived as moderately constraining. Some respondents disagreed that both time and money would be needed for research and development institutions to establish markets for lesquerella products.

Participants expressed concern about the economic feasibility of marketing lesquerella. Respondents perceived four components as highly constraining: procurement procedures that are competitive with imported oils, the cost of establishing and procuring a dependable supply of high quality seed, expenditures incurred by research and development institutions to formulate new industrial applications for lesquerella products, and the time and the money needed by research and development institutions to establish markets for lesquerella products.

Seventeen components were rated as moderate economic hindrances. Some disagreement occurred concerning the economic feasibility and institutional permissibility of government services that would affect the procurement of lesquerella seed for processing, such as grading standards and market information. One-third of the respondents disagreed that proprietary rights would hinder the economic and institutional dissemination of lesquerella processing information.

Table 12. Mean Rating of Respondents to Lesquerella Delphi Survey for PMC Marketing Subsystem.

Marketing component[2]	Mean rating[1]		
	Technically possible	Economically feasible	Institutionally permissible
Procurement resources	2.88	2.94	3.00
Dependable supply	2.77	2.86	4.11
Procurement financing	3.33	3.53	3.22
Government services and requirements (procurement)	3.21	3.14	3.67
Market information for procurers	4.19	4.06	3.78
Transportation and storage	3.40	3.40	3.89
Processing resources	4.13	3.87	4.56
Processing equipment	3.71	3.79	4.11
Information exchange institutions	4.33	4.13	3.78
Energy availability	3.67	3.07	4.33
Processing research	3.71	4.21	3.78
Information dissemination programs	3.33	3.07	3.44
Coproduct use	3.36	3.50	3.22
Managerial ability	3.50	3.00	3.89
Distribution resources	3.15	3.33	3.67
Distribution financing	3.42	3.31	3.11
Product market information	3.14	3.14	2.86
Product transportation and storage	4.14	3.86	3.88
Product R&D institutions	3.13	2.53	4.33
Market R&D institutions	3.21	2.85	3.75
Government services and regulations (marketing)	4.00	3.75	3.67

[1]Rating scheme: 1.00-1.99, completely constrained; 2.00-2.99, highly constrained; 3.00-3.99, moderately constrained; and 4.00-5.00, no substantial constraints.

[2]Corresponds to a Delphi survey question and accompanying summary statements. See appendix C, table C1.

Respondents only identified one highly constraining factor related to institutional permissibility. They considered the uncertainty about the relationship between lesquerella and castor feedstocks as a major market information problem. Respondents identified no specific regulations or institutional barriers for marketing lesquerella, but the lack of funding for research and commercialization is limiting lesquerella development. Some divergence of opinion existed over the availability of financing for lesquerella procurement.

Consumption. To date, the consumption subsystem has received little research attention. As a result, the respondents rated all the factors as moderately to highly constraining (table 13).

End-product competition was rated as highly constraining, both technically and economically. Lesquerella products will need a clear and demonstrated advantage to compete in the marketplace. Some respondents disagreed on the cost of educating consumers about lesquerella's advantages. Respondents failed to identify any major hindrances regarding institutional permissibility. However, they felt that effort is needed to educate potential consumers of lesquerella products about the advantages of lesquerella as a domestic, renewable resource.

Table 13. Mean Rating of Respondents to Lesquerella Delphi Survey for PMC Consumption Subsystem.

Consumption component[2]	Mean rating[1]		
	Technically possible	Economically feasible	Institutionally permissible
End-product competition	2.67	2.57	3.13
Market size	3.33	3.14	3.89
Consumer awareness	3.57	3.25	3.67
Product versatility	3.07	3.15	3.78

[1]Rating scheme: 1.00-1.99, completely constrained; 2.00-2.99, highly constrained; 3.00-3.99, moderately constrained; and 4.00-5.00, no substantial constraints.

[2]Corresponds to a Delphi survey question and accompanying summary statements. See appendix C, table C1.

• • Conclusions and Recommendations • •

Many potential hindrances to lesquerella commercialization exist, but none present an insurmountable challenge. Therefore, additional resources can be fruitfully employed to enhance lesquerella's commercial prospects. Public sector research and development, plus cooperative private sector involvement, are needed to move lesquerella toward the marketplace.

The conclusions and recommendations in this section are divided into five parts: production, processing, product development, economics and infrastructure development, and needed resources.

Production

Even though the Delphi respondents considered production the least constrained subsystem, significant avenues for progress exist.

An expanded plant improvement program is warranted. The results achieved thus far with *L. fendleri* are encouraging, but more selection and breeding work is essential. Considerable genetic variation has been observed in *L. fendleri* and other species within the genus. This variability can provide plant breeders with opportunities to improve the plant characteristics and growth habit needed in a commercial oilseed crop.

Scientists should be able to increase yields through a number of different characteristics, for example, seed size, number of seeds per plant, more uniform seed maturity, and taller and more erect plants. Enhanced seedling vigor will help lesquerella compete with weeds.

Oil content and composition are also important. Successfully breeding commercial *L. fendleri* varieties with more than 80 percent lesquerolic acid in the oil would diminish substantially the need to separate the fatty acids. This would significantly improve the economics of manufacturing lesquerella products.

If commercial production of *L. fendleri* is successful, efforts to domesticate and commercialize other lesquerella species should receive more attention. For example, species that produce densipolic and auricolic acids could supply different raw materials for new and existing industrial applications.

Cultural practices need additional attention. Further research on planting methods will help farmers develop a reliable system for planting that promotes uniform seedling establishment and growth. Study of lesquerella's fertilizer requirements, as well as methods and timing of fertilizer applications, will further define lesquerella production.

Weed control warrants investigation. Further research could evaluate different methods of control, including cultural practices, herbicides, and integrated pest management. The lack of approved chemicals is a major hindrance for new crops such as lesquerella.

Research into water management practices to optimize yield and oil content and composition is needed. Various irrigation techniques—such as the low energy, precise application system—should be studied to determine the most cost-effective and environmentally friendly method. Water use will continue to be an important issue for agriculture in the West.

Finally, scientists should evaluate *L. fendleri* production in other areas of the United States. A broader perspective of the crop's potential is warranted. In addition, species native to Alabama and Tennessee, Oklahoma and eastern Texas, and other parts of the West may offer opportunities for crop varieties adapted to various regions of the country. An effort to collect new germplasm is being organized to more fully evaluate the potential of different, previously untested lesquerella species.

Processing

Like many other oilseeds, lesquerella seed would be conditioned for oil extraction. More research on flaking lesquerella seed for full solvent extraction is needed before this process can be recommended for the crop. Further pilot-plant tests would help define the optimal conditions for preparing flakes, press cake, and extruded collets.

More information is needed to verify that the thioglucosidase enzyme can be consistently and completely inactivated during processing. According to previous studies, the enzyme can be inactivated by cooking or extrusion during seed preparation. Further research should include analysis of processed seed material for glucosinolates and the

enzyme-produced isothiocyanates and thiooxazolidones. Oil samples should also be tested for their glucosinolate content.

Pilot-scale tests suggest that lesquerella seed can be processed in existing oilseed crushing plants designed for either prepress-solvent extraction or extrusion followed by full solvent extraction. However, further research is needed to ascertain the relative efficiency of extracting oil from flakes, press cake, or collets. The quality of the resulting oils is also worth analyzing.

More work on solvent extraction should be undertaken to determine optimum particle size, quantity of solvent needed to recover the maximum amount of oil, and percolation and drainage times. These factors will minimize residual oil left in the meal and fine particles of meal contaminating the oil.

Demonstrations at pilot and commercial plants would be useful in providing information on lesquerella processing to the oilseed industry. Companies building new plants may want to consider extrusion equipment to prepare the seed for solvent extraction. Mills could use lesquerella to lengthen their crushing season by processing the crop prior to the annual maintenance period, where the facilities are cleaned and prepared for crushing edible oilseeds.

Laboratory research has shown that lesquerella oil can be degummed and bleached. However, pilot-plant tests are needed to evaluate commercial procedures for degumming, alkali refining, and bleaching of the oil. Ultimately, how the oil is used by industry will determine its processing and refining requirements.

The composition of recovered gums should be investigated. They could be used in food manufacturing, as are many gums from vegetable oils. Similarly, soapstocks from alkali refining should be characterized as to composition and possible uses.

Bleaching is necessary because of the reddish color of crude lesquerella oil. Pilot-scale tests, using readily available bleaching clays, could evaluate oil color and yield as a function of the type of clay, its concentration, and bleaching time and temperature. Quality standards for crude, degummed, and refined oils would facilitate market acceptance and large-scale commercial transactions.

Product Development

Chemists have conducted only minimal research on uses of lesquerella oil. Therefore, tests comparing lesquerella and castor oils and their derivatives need to be a high priority. Such analysis could define the chemical properties and relationships of the compounds.

The functionality of lesquerella oil and its derivatives for use in products must be clearly demonstrated. New industrial applications could expand the market for hydroxy oils beyond traditional uses. An example of a potential opportunity is dodecanedioic acid, which would be used in manufacture of nylon-12.

Feeding trials are needed to determine the value of lesquerella meal as a protein supplement. Recently initiated studies with rats and chicks will assess the nutritional quality of lesquerella meal from various types of crushing plants. Feeding trials with beef cattle are planned that will examine the palatability of the meal, weight gain and feed efficiency of the animals, and the effects of glucosinolates, isothiocyanates, and thiooxazolidones on the acceptability of the meal. Later tests could analyze use of the meal in swine rations.

Some lesquerella oil may be used by cosmetics firms. They prefer the high quality oil extracted by expellers. However, this process leaves residual oil in the press cake. Like castor oil, the hydroxy acids may act as a laxative. The effect of press cake meal on cattle should be investigated. In addition, quality parameters should be established for the meal to facilitate commercial use.

A cosmetics firm recently expressed interest in purchasing commercial quantities of lesquerella oil in 1993. Even with the resources suggested by the task force for research and development, it will be difficult to meet their request.

Economics and Infrastructure Development

Preliminary estimates of the value of lesquerella oil and seed, and of farm operating expenses, indicate that farmers in Arizona could economically produce lesquerella. However, more definitive analysis is needed.

Respondents to the Delphi survey indicated concern that insufficient market information exists for lesquerella seed, oil, fatty acids, and meal. Furthermore, market information was perceived as inadequate on some input factors, such as quality seed for planting. Therefore, market information systems need to be developed to serve new crops and their industrial products, like lesquerella and its derivatives.

Public sector scientists interested in lesquerella need to nurture relationships with individuals in the private sector. Firms with potential interest in lesquerella oil need to be encouraged to participate in research and development through cooperative agreements. Research objectives, market needs, new products, and potential obstacles are more likely to be properly identified and addressed in a joint activity.

For lesquerella to be a success, both the public and private sectors will need to contribute resources toward its development. Many of the moderately constraining factors identified in the Delphi survey can only be addressed by a public-private demonstration project undertaken on at least a semicommercial basis.

Needed Resources

The task force believes lesquerella has significant potential as a source of hydroxy fatty acids for industrial products. However, additional resources must be allocated to transform this potential into reality. Funding is needed to address the hindrances identified by the task force and Delphi survey participants.

Based on the potential identified in this assessment, the task force recommends a significant increase in resources; not a huge effort but one commensurate with lesquerella's promise. We suggest that 4.5 new scientist years (SYs) be devoted to lesquerella development for the next 5 years, with annual funding of $800,000.

Two SYs should be devoted to plant improvement and development of cultural and management practices. Two SYs should be allocated to product development research on items like greases, lubricants, chemical intermediates, and polymers. One-half SY should support marketing, infrastructure development, and formation of public-private sector partnerships.

Cultivating precommercial cooperation activities among government, academia, and private industry is necessary. Often, such cooperative efforts require all parties to contribute technical and financial resources. Some additional public funding may be needed to activate such partnerships or consortia.

The task force feels that significant progress can be made with this level of support. The investment will yield good dividends to investors, be they public or private.

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• • Appendix A • •
Uses of Castor Oil

Castor oil is one of the oldest industrial products from agriculture. Ancient Egyptians used castor oil in their lamps and as a skin and hair treatment [61, 62].

In modern times, manufacturers have developed many products that contain castor oil or its derivatives. The oil is used directly in a number of items, such as lubricants, soaps, adhesives, inks, metal drawing and casting lubricants, cutting oils, and cosmetics [34]. However, most castor oil is further processed by the chemical industry. The resulting derivatives are used in a wide range of applications (table A1). The use of castor oil as a laxative has declined through the years and is now of minor importance [63].

The unique lubricating properties of castor oil and its derivatives make them invaluable for military purposes. The hydrogenated oil imparts thickening properties in grease formulations and sebacic acid serves as a lubricant for aircraft hydraulics. Because of these uses, the Department of Defense continues to include ricinoleic and sebacic acid products in its Strategic and Critical Materials Program. As of September 30, 1988, DOD listed 8.8 million pounds of ricinoleic and sebacic acid products as the target amount for the stockpile. However, current inventory is slightly over 5 million pounds [64], about 55 percent of the target.

The Strategic and Critical Materials Stock Piling Act mandates that a stock of strategic and critical materials be maintained to decrease dependence upon foreign sources of supply in times of national emergency. Since the early 1970s, all of the castor oil used in the United States has been imported. The Act requires that the stockpile be sufficient to cover U.S. needs for at least 3 years of an emergency. In addition to maintaining stocks of materials, the Act also requires actions to encourage the conservation and development of domestic sources of strategic and critical materials [65].

Table A1. Major Uses of Castor Oil.

Derivative	Use[1]
Nylon-11	Engineering plastics and powder coatings
Hydrogenated oil	Lubricating greases for cars, trucks, boats, railcars, aircraft, and industrial equipment
Dehydrated oil and fatty acids	Coatings, inks, sealants, and related products
Sebacic acid	Aircraft lubricants, plasticizers for vinyl, and nylon-610
Ethoxylated oil and ethoxylated, hydrogenated oil	Surfactants, emulsifiers, textile processing, and agricultural chemicals
Sulfated and sulfonated oil	Surfactants and emulsifiers
Polyurethanes	Electrical and telecommunication casting resins and coatings
Esters and derivatives	General plasticizers
Oxidized and polymerized oil	Plasticizers for coatings, inks, and sealants

[1]Listed in order of importance.

Source: [62].

• • Appendix B • •
Industrial Uses of Fats and Oils

Table B1. Industrial Uses of Fats and Oils, 1979/80-1988/89.

Fat or oil	Total consumption	Total edible	Total inedible	Soap	Paint or varnish	Feed	Resins and plastics	Lubricants[1]	Fatty acids	Other inedible
					Million pounds					
Castor oil										
1979/80[2]	89.9	—	89.9	—	d	—	d	5.2	d	75.2
1980/81	86.5	—	86.5	—	d	—	d	5.5	d	69.3
1981/82	82.3	—	82.3	—	d	—	16.4	d	—	56.6
1982/83	71.9	—	71.9	d	d	—	11.9	d	—	57.5
1983/84	71.0	—	71.0	d	d	—	10.3	d	—	58.6
1984/85	67.1	—	67.1	—	d	—	11.0	5.2	d	d
1985/86	59.9	—	59.9	d	d	—	4.5	d	d	d
1986/87	70.4	—	70.4	d	4.6	—	4.2	5.6	d	53.8
1987/88	74.6	—	74.6	d	4.3	—	4.8	6.1	d	59.0
1988/89	59.2	—	59.2	d	4.8	—	4.5	6.2	—	43.2
Coconut oil										
1979/80	663.4	254.2	409.2	172.7	d	—	—	—	106.5	d
1980/81	789.7	337.6	452.1	179.9	2.0	—	—	—	102.1	168.1
1981/82	749.4	337.9	411.5	165.5	1.7	—	—	—	98.8	145.5
1982/83	800.2	339.4	460.8	185.2	1.2	—	d	d	100.4	d
1983/84	793.4	299.5	493.9	237.8	1.5	—	d	—	102.8	202.0
1984/85	650.5	274.5	376.0	137.6	d	—	d	d	63.9	d
1985/86	634.7	332.8	301.9	123.2	d	—	d	d	59.7	d
1986/87	858.2	319.4	538.8	216.1	d	—	d	d	95.7	d
1987/88	788.6	233.4	555.4	213.8	d	—	7.2	d	131.4	d
1988/89	688.8	211.2	477.6	130.6	1.4	d	14.6	d	121.9	206.6
Cottonseed oil										
1979/80	686.2	677.8	8.4	d	—	—	—	d	—	d
1980/81	560.1	555.0	5.1	d	d	—	—	d	—	d
1981/82	608.1	602.7	5.4	d	—	—	—	d	—	d
1982/83	637.8	634.0	3.8	d	d	d	d	d	—	d
1983/84	568.9	558.2	7.1	—	d	d	—	d	—	d
1984/85	630.1	607.4	22.8	d	—	d	d	d	—	d
1985/86	639.4	627.1	12.3	d	d	d	—	d	—	d
1986/87	610.4	594.2	16.2	d	d	—	d	d	—	d
1987/88	805.3	791.0	14.3	d	d	—	d	d	—	d
1988/89	d	916.7	d	d	d	d	d	d	—	d
Linseed oil										
1979/80	160.0	—	160.0	—	103.7	—	19.6	na	d	d
1980/81	127.6	—	127.6	—	69.6	—	23.3	na	d	d
1981/82	92.7	—	92.7	—	42.4	—	20.9	d	d	d
1982/83	97.6	—	97.6	—	50.1	—	20.4	d	d	d
1983/84	121.2	—	121.2	—	56.5	d	27.7	d	d	34.1
1984/85	166.0	—	166.0	—	113.5	—	26.3	d	d	24.4
1985/86	176.9	—	176.9	—	131.0	—	29.7	d	d	d
1986/87	280.8	—	280.8	—	187.6	—	d	d	d	d
1987/88	159.3	—	159.3	—	85.5	—	31.0	d	d	40.5
1988/89	154.9	—	154.9	—	101.6	—	23.1	d	d	28.2

See footnotes at end of table.

Table B1 cont.

Fat or oil	Total consumption	Total edible	Total inedible	Soap	Paint or varnish	Feed	Resins and plastics	Lubri-cants	Fatty acids	Other inedible
					Million pounds					
Palm oil										
1979/80	283.4	255.2	28.2	d	—	—	—	d	d	d
1980/81	321.3	291.4	29.9	d	—	—	—	d	d	d
1981/82	296.1	253.8	42.3	d	—	—	—	d	d	d
1982/83	306.0	272.3	33.7	d	—	d	d	—	d	d
1983/84	311.9	287.5	24.4	d	—	d	—	d	d	23.8
1984/85	300.8	269.7	31.3	d	—	d	—	—	d	d
1985/86	398.1	364.0	34.1	d	—	d	—	d	d	d
1986/87	317.9	278.7	39.2	d	d	d	d	d	d	d
1987/88	242.6	197.5	45.1	d	d	d	d	d	d	d
1988/89	247.0	203.8	43.2	d	—	d	d	—	d	d
Safflower oil										
1979/80	29.2	26.2	3.0	—	2.0	—	—	—	—	1.0
1980/81	21.2	19.2	2.0	—	1.3	—	—	—	—	0.7
1981/82	16.2	14.0	2.2	—	1.3	—	—	—	—	0.9
1982/83	d	d	1.8	—	d	—	d	—	—	d
1983/84	d	d	2.2	—	d	—	d	—	—	d
1984/85	d	d	3.0	—	d	d	d	—	—	d
1985/86	d	d	2.4	—	d	—	d	—	—	d
1986/87	32.9	30.3	2.6	—	d	—	d	—	—	d
1987/88	d	d	d	—	d	—	d	d	—	d
1988/89	d	d	d	—	d	—	d	—	—	d
Soybean oil										
1979/80	8,698.2	8,493.1	205.1	—	51.9	—	79.8	—	21.2	52.2
1980/81	8,812.5	8,610.2	202.3	—	45.7	—	70.9	—	22.8	62.9
1981/82	9,335.4	9,132.6	202.8	—	38.9	—	93.7	—	21.5	48.7
1982/83	9,487.0	9,282.3	204.7	—	38.0	d	96.3	d	15.9	50.4
1983/84	9,476.4	9,245.4	231.0	d	39.3	d	109.6	d	20.8	61.5
1984/85	10,423.5	10,171.6	251.5	10.2	51.7	d	92.9	d	29.1	60.4
1985/86	10,283.3	10,003.7	279.5	d	59.5	d	98.7	d	31.5	d
1986/87	10,512.2	10,212.7	299.5	d	63.2	d	109.2	d	d	65.3
1987/88	10,714.5	10,429.1	285.3	2.7	54.1	d	106.1	d	d	72.3
1988/89	9,917.6	9,635.8	281.8	1.5	34.9	d	123.7	d	d	68.2
Sunflower oil										
1979/80	85.1	84.3	0.8	—	—	—	—	—	—	0.8
1980/81	82.2	78.9	3.3	—	—	—	—	—	—	3.3
1981/82	90.2	88.8	1.4	—	—	—	—	—	—	1.4
1982/83	74.9	73.3	1.6	—	d	—	d	—	—	d
1983/84	85.8	84.0	1.8	—	d	—	d	—	—	d
1984/85	116.4	110.4	6.0	—	—	—	d	—	—	d
1985/86	88.5	85.9	2.6	—	d	—	d	—	—	d
1986/87	76.8	75.3	1.5	—	d	—	d	—	—	d
1987/88	62.4	59.0	3.6	—	d	—	d	—	—	d
1988/89	41.6	38.4	3.2	—	d	—	d	—	—	d

Table B1 cont.

Fat or oil	Total consumption	Total edible	Total inedible	Soap	Paint or varnish	Feed	Resins and plastics	Lubri-cants	Fatty acids	Other inedible
					Million pounds					
Tall oil										
1979/80	1,312.1	—	1,312.1	3.0	11.4	—	9.6	5.7	1,208.2	74.2
1980/81	1,334.0	—	1,334.0	3.7	10.9	—	14.8	4.9	1,205.9	93.8
1981/82	1,185.1	—	1,185.1	3.4	15.9	—	17.2	4.1	1,096.2	48.3
1982/83	1,151.2	—	1,151.2	4.0	29.7	—	21.1	4.3	1,041.5	54.5
1983/84	1,228.0	—	1,228.0	d	32.9	—	24.7	d	1,095.8	63.5
1984/85	1,086.8	—	1,086.8	d	19.5	d	16.0	d	994.2	41.1
1985/86	1,143.4	—	1,143.4	12.8	17.0	—	15.6	12.0	1,055.2	30.8
1986/87	1,227.0	—	1,227.0	12.2	d	—	15.7	12.9	1,152.6	19.2
1987/88	1,269.4	—	1,269.4	16.8	23.3	—	20.9	9.6	1,181.1	17.8
1988/89	1,234.3	—	1,234.3	8.3	31.8	—	18.0	8.1	1,157.3	10.8
Tung oil										
1979/80	15.7	—	15.7	—	10.4	—	3.0	—	—	2.3
1980/81	16.6	—	16.6	—	8.3	—	3.7	—	—	4.6
1981/82	14.6	—	14.6	—	5.8	—	3.2	—	—	5.6
1982/83	12.2	—	12.2	—	5.3	—	2.8	—	—	4.0
1983/84	19.7	—	19.7	—	5.6	—	3.4	—	—	10.8
1984/85	12.4	—	12.4	—	5.1	—	4.5	—	—	2.9
1985/86	11.6	—	11.6	—	5.2	—	4.3	—	—	2.1
1986/87	12.2	—	12.2	—	d	—	6.1	—	—	d
1987/88	14.8	—	14.8	—	3.6	—	8.8	d	—	d
1988/89	7.7	—	7.7	—	3.5	—	1.8	—	—	2.4
Fish oil										
1979/80	25.1	—	25.1	—	7.8	—	d	d	d	d
1980/81	19.0	—	19.0	—	6.4	—	d	3.8	d	3.7
1981/82	15.7	—	15.7	—	4.5	—	d	2.1	d	4.0
1982/83	17.9	—	17.9	—	d	d	d	d	d	5.1
1983/84	22.3	—	22.3	—	d	—	d	d	d	d
1984/85	13.9	—	13.9	d	—	d	d	d	d	d
1985/86	14.5	—	14.5	—	d	—	d	d	—	d
1986/87	16.1	—	16.1	—	d	—	d	d	—	d
1987/88	12.9	—	12.9	—	d	—	d	d	d	8.4
1988/89	16.9	—	16.9	—	0.1	—	d	1.4	d	11.9
Lard										
1979/80	526.9	474.7	52.2	—	—	—	—	8.0	—	44.2
1980/81	480.2	414.8	65.4	—	—	—	—	8.3	—	57.1
1981/82	361.2	311.2	50.0	—	—	—	—	5.8	—	44.2
1982/83	367.5	284.1	83.4	—	—	d	—	5.3	d	d
1983/84	366.8	313.7	53.1	—	—	d	—	6.1	d	d
1984/85	378.5	328.7	50.0	—	—	d	—	d	d	d
1985/86	405.8	355.0	50.8	—	—	d	—	7.2	d	d
1986/87	301.2	240.9	60.3	d	—	d	—	6.2	d	d
1987/88	347.5	280.3	66.9	d	—	d	—	8.4	d	d
1988/89	389.9	324.5	65.4	—	—	d	—	d	d	d

Table B1 cont.

Fat or oil	Total consumption	Total edible	Total inedible	Soap	Paint or varnish	Feed	Resins and plastics	Lubri-cants	Fatty acids	Other inedible
					Million pounds					
Edible tallow										
1979/80	714.5	680.4	34.1	—	—	—	d	d	d	d
1980/81	767.1	740.2	26.9	d	—	—	d	d	d	d
1981/82	741.5	701.8	39.7	d	—	—	d	d	d	d
1982/83	664.7	622.7	42.0	d	—	d	d	d	d	d
1983/84	846.4	784.0	62.4	d	—	d	d	d	d	d
1984/85	1,009.5	949.7	48.4	d	—	—	d	—	d	d
1985/86	1,080.2	1,020.9	59.2	d	—	—	—	d	d	d
1986/87	979.2	910.6	68.6	d	—	—	d	d	d	d
1987/88	954.3	863.6	90.5	d	—	—	d	d	d	d
1988/89	923.3	779.2	144.1	d	—	d	d	d	d	d
Inedible tallow										
1979/80	2,983.6	—	2,983.6	658.2	—	1,219.6	—	108.5	814.6	182.7
1980/81	2,984.1	—	2,984.1	617.4	—	1,307.9	—	69.0	813.3	176.5
1981/82	2,893.8	—	2,893.8	549.6	—	1,393.1	—	53.1	736.9	161.1
1982/83	2,808.7	—	2,808.7	557.6	—	1,402.5	—	54.9	618.5	115.5
1983/84	2,952.1	—	2,952.1	631.5	—	1,357.0	—	56.4	700.2	206.9
1984/85	2,806.9	—	2,806.9	551.0	—	1,348.4	—	64.5	767.3	75.9
1985/86	2,878.5	—	2,878.5	492.3	—	1,550.5	—	62.8	733.4	39.5
1986/87	3,040.9	—	3,040.9	543.6	—	1,698.9	—	70.3	693.6	35.1
1987/88	3,137.8	—	3,137.8	502.0	—	1,820.3	—	69.9	712.6	33.0
1988/89	3,086.7	—	3,086.7	374.9	—	1,925.4	—	70.3	680.0	36.1
Total use										
1978/79	17,440.4	11,607.2	5,833.2	872.7	251.3	1,389.3	136.5	165.9	2,282.7	734.8
1979/80	17,346.1	11,828.3	5,517.8	842.7	199.9	1,301.7	125.6	171.5	2,206.2	670.2
1980/81	17,457.9	11,908.0	5,549.9	808.1	154.3	1,386.7	129.0	125.4	2,195.0	751.4
1981/82	17,476.7	12,308.2	5,168.5	740.2	118.9	1,447.5	158.1	86.4	2,003.2	614.2
1982/83	17,586.7	12,464.8	5,127.1	796.1	137.8	1,477.5	170.1	87.2	1,843.2	615.4
1983/84	17,956.8	12,527.9	5,428.9	868.2	147.4	1,446.8	199.4	104.2	1,993.5	666.9
1984/85	18,915.0	13,784.5	5,130.5	785.6	210.8	1,465.5	166.3	100.1	1,931.5	470.8
1985/86	19,249.6	13,972.6	5,277.0	754.9	228.0	1,705.7	173.4	103.4	1,968.9	342.6
1986/87	d	d	5,990.6	d	d	d	d	d	d	d
1987/88	20,241.2	14,175.5	6,065.7	868.6	179.1	1,967.6	196.3	107.8	2,203.8	542.8
1988/89	19,426.7	13,542.0	5,884.7	744.5	180.3	2,079.3	202.3	115.8	2,074.1	488.4

— = Not applicable or zero.
d = Data withheld to avoid disclosing figures for individual companies.
na = Not available.
[1]Category includes lubricants and similar oils.
[2]Crop year runs from October 1 to September 30.
Source: [10].

• • Appendix C • •
Delphi Survey

The following people completed questionnaires on the prospects of commercializing lesquerella.

Dr. Richard Baldwin
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Cargill Company
Minneapolis, Minnesota

Dr. Joseph S. Boggs
Product Development
Industrial Chemical Division
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Dr. Raymond Brigham
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Dr. Ken Carlson
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Dr. David Dierig
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Mr. Fred Harper
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Dr. Joseph Hoffmann
University of Arizona
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Dr. Quentin Jones (partial)
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Dr. Steven J. Knapp (partial)
Oregon State University
Department of Crop Science
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Dr. Paul Knowles
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Dr. Dennis T. Ray
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Dr. Joseph C. Roetheli
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Dr. John Rothfus
USDA Agricultural Research Service
National Center for Agricultural Utilization Research
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Dr. Anson E. Thompson
USDA Agricultural Research Service
U.S. Water Conservation Laboratory
Phoenix, Arizona

Mr. Louis van Soest
Coordinator, Agricultural Crops
Center for Genetic Resources
Wageningen, Netherlands

Dr. Ivan A. Wolff
USDA Agricultural Research Service
Eastern Regional Research Center
Philadelphia, Pennsylvania

Table C1. Lesquerella Delphi Questions and Summary Statements.

Question	Summary statement		
	Technically possible	Economically feasible	Institutionally permissible
Production subsystem			
Can sufficient land be allocated to lesquerella within its agroclimate?	Suitable land is available but its allocation is dependent upon the new crop's profitability relative to competing crops	If lesquerella can be shown to yield a profit relative to cotton and castor oil, land will be allocated	Government support programs on major crops are obstacles to new crops, such as lesquerella
Can sufficient water be allocated to lesquerella within projected production areas?	Because lesquerella appears to have competitively low water requirements, water allocation is not foreseen as a problem	Lesquerella as a low water user should compete well in the allocation of water	Because lesquerella appears to have lower water requirements than traditional crops in SW, existing water regulations are not foreseen as a problem
Can all aspects of lesquerella production receive adequate financing from producers, lenders, the oilseed industry, etc.?	Money is available if lesquerella is profitable but subject to some reluctance common to new crops	Financing will be difficult until profit is demonstrated but possible with government support or vertical integration	Money is available for lesquerella but financing is subject to some reluctance common to new crops unless government or industry support is available
Do necessary techniques and materials exist to control pests and disease?	No particular problem with pest management is foreseen	No problem now but if chemical control becomes necessary it is costly to get chemicals relabeled for new crops	Getting label approval for chemicals on lesquerella is expected to be difficult because of government regulations and environmental concerns
Can sufficient quantities of high quality lesquerella seed be obtained from dependable sources?	Although large quantities of seed are not presently available, sufficient quality seed will probably be available when needed	No particular problem foreseen in supplying sufficient lesquerella seed, especially with a little government assistance	—
Are fertilizers available for lesquerella?	Although little work has been done on fertilizers for lesquerella, no problems are foreseen	Use of fertilizers for lesquerella should not be too costly	—
Can the production inputs for lesquerella be transported and stored adequately?	Input transportation and storage is not seen as a problem because of experience with similar crops	Input transportation and storage for lesquerella seems to be competitive with other crops	—
Do potential producers of lesquerella possess sufficient managerial abilities?	Potential producers have the managerial ability but will need some time to develop knowledge and experience specific to lesquerella	With initial educational and risk support, producers should be able to manage lesquerella adequately	Potential producers have the managerial ability to grow lesquerella but the resistance to change and learn a new crop will have to be overcome
Does lesquerella require special production equipment?	Conventional equipment, possibly with slight modification to handle the small seed, should be adequate	Existing farm machinery can be used successfully for lesquerella	—

See footnote at end of table.

Table C1 cont.

Question	Summary statement		
	Technically possible	Economically feasible	Institutionally permissible
Can energy requirements for lesquerella production be satisfied?	No problem is foreseen in satisfying the energy requirements for lesquerella	Energy requirements for lesquerella appear to be competitive with existing crops	—
Is input market information for lesquerella readily available to producers?	Little is known about the input market, so this area must be developed for lesquerella	Input market information is critical and must be developed for lesquerella	—
Do government services and regulations exist that would affect lesquerella production?	Government clearance of chemicals for use on lesquerella is the only major difficulty foreseen in this area	Current government relationships effecting lesquerella seem comparable to other crops	Government clearance of chemicals for use on lesquerella is the only major difficulty foreseen in this area
Are agricultural research programs available and willing to deal with critical problems of lesquerella production?	Increased funding for research programs is needed to speed the commercialization of lesquerella	More funding is needed for lesquerella research	The needed increase in government funding for research on lesquerella will continue to be a constraint because of a very small constituency
Are information dissemination programs available from either public or private sources to provide producers with good and timely information on lesquerella production?	The extension service can handle the dissemination once the information is developed	Existing agricultural information dissemination programs can also handle lesquerella with little cost	The extension program can handle the dissemination once the information is developed
Do institutions exist to facilitate exchanges of lesquerella-specific information?	No formal structures exist for lesquerella but they can be rapidly developed when the need arises	If lesquerella is profitable, crop-specific exchanges will develop with little cost	No formal structures exist for lesquerella but they can be rapidly developed when the need arises
Is there sufficient farm labor available when needed for lesquerella production?	Labor requirements for lesquerella seem compatible with current labor patterns	Farm labor requirements are seen to be compatible with traditional crops	Labor requirements for lesquerella seem compatible with current labor patterns
Is market information for lesquerella available to producers on a timely basis?	Although no market information for lesquerella is now available, it can be developed over time	Market information for lesquerella is tied to the oils industry and may be expensive to develop for the producer	When market information for lesquerella becomes available, no institutional obstacles are apparent in its distribution to producers
Other production considerations?	Germplasm selections and consistent stands may take several years With a small allocation of resources, it appears that lesquerella can achieve commercialization	—	—

Table C1 cont.

Question	Summary statement		
	Technically possible	Economically feasible	Institutionally permissible
Marketing subsystem			
Can sufficient procurement resources be allocated to move lesquerella from local market outlets through the rest of the marketing channel?	If the chemical companies specializing in seed oils demand lesquerella, procurement resources will be allocated	Procurement procedures that are competitive with imported oils must be set up	—
Can a dependable supply of lesquerella be obtained with regard to both quantity and quality?	Although there is no supply of lesquerella now, it is probable that a dependable and consistent crop can be produced	This is an unknown which will be driven by income potential	—
Can all aspects of lesquerella procurement be adequately financed?	If industry is buying lesquerella, procurement financing should be no different for lesquerella than for other crops	If industry wants lesquerella, financing procurement is not foreseen as a problem	Government needs to assist with the initial procurement financing
Do government services and requirements exist at any level that would affect lesquerella procurement?	Government is not now, and need not be, involved in the procurement process of lesquerella	Government is not currently involved in the procurement area but problems may arise with future legislation	Government is not now, and need not be, involved in the procurement process of lesquerella
Is market information on production volume, prices, alternative commodities, etc., readily available to potential procurers of lesquerella?	Little market information is available to procurers but as lesquerella develops, the development of market information is expected to be straightforward	Market information on related products is readily available but little is known about lesquerella	—
Can lesquerella be transported to and stored by appropriate processing facilities?	The only difficulties expected in transportation and storage of lesquerella have to do with the small size of the seed and of the crop	Transporting lesquerella to processing facilities and storage seem competitive	—
Can sufficient processing resources be allocated to lesquerella?	Initial difficulties are expected because of the small volume of lesquerella as its market develops	Initially, the low volume of lesquerella available will limit the processing resources allocated to lesquerella	—
Is equipment available for processing lesquerella?	Existing equipment should be able to handle lesquerella	Equipment to process lesquerella is available and will be used if industry sees the profit	—
Do institutions exist to facilitate the exchange of lesquerella-specific processing information?	Although no institutions now exist concerning lesquerella, existing relationships can be expanded to cover this function	Although lesquerella-specific processing information is not now available, this is not seen as a major problem	Although no institutions now exist concerning lesquerella, existing relationships can be expanded to cover this function

Table C1 cont.

Question	Summary statement		
	Technically possible	Economically feasible	Institutionally permissible
Are energy and other inputs readily available for the processing of lesquerella?	Energy needs for processing lesquerella are expected to be comparable to other oilseeds	Processing energy costs are not known but are expected to be competitive	—
Are processing research programs available and willing to deal with critical problems related to lesquerella processing?	Processing research programs are in place but need some additional funding	Processing research funds for new small volume crops, such as lesquerella, are necessary but difficult to get	Processing research programs need additional funding and more interaction between industry and the public sector
Are information dissemination programs available from either private or public sources to provide processing information for lesquerella processing?	Information dissemination mechanisms exist but the information is lacking	Information dissemination on processing lesquerella may be difficult because of proprietary industry and lack of network among participants	Proprietary industry may inhibit the flow of processing information
Does technology exist to utilize byproducts and/or dispose of waste resulting from lesquerella processing?	The meal may be a coproduct, pending additional research on the glucosinolates	Costly research is needed to determine if the meal can be used	The utilization of a more benign meal from lesquerella is expected to be its advantage over castor
Do potential processors of lesquerella possess sufficient managerial ability?	Managerial ability is sufficient, although risk taking is a major factor	Although managerial ability is sufficient among potential processors, government support would reduce the aversion to risk	—
Other processing considerations?	None to report	None to report	—
Can sufficient distribution resources be allocated to industrial feedstocks of end products from lesquerella?	If lesquerella oil is accepted by the seed oil industry, the allocation of distribution resources should be like any other industrial oil	No problem foreseen in the distribution of the feedstocks and/or end products of lesquerella if they are competitive	The saving of foreign exchange (domestic lesquerella verses imported castor) will favor allocation to lesquerella, all other things equal
Can all aspects of lesquerella distribution be adequately financed?	Financing for lesquerella distribution is available by transferring funds from castor oil or with outside support	Financing distribution of lesquerella products may be hindered by resistance to change and risk of a new product	Financing for lesquerella distribution is expected to be difficult because the castor industry has little inducement to change
Is market information regarding lesquerella feedstock or end-product distribution readily available?	This is unknown for lesquerella; developing information on the relationship with castor oil and other marketing information should not be difficult	Marketing information for lesquerella products is not in place but would be feasible to develop	Uncertainty about the relationship between lesquerella and castor feedstocks is a major market information problem
Can the processed lesquerella product be adequately transported and stored?	Lesquerella product should be handled about like any other oilseed product	Transportation and storage of lesquerella product is expected to be competitive	—

Table C1 cont.

Question	Summary statement		
	Technically possible	Economically feasible	Institutionally permissible
Do research and development institutions exist that could find industrial applications for lesquerella?	The expertise is available but it needs to be redirected to deal with lesquerella	Research for new industrial applications of lesquerella will be costly, yet necessary, to expand the market beyond substitution	The expertise is available but it needs to be redirected to deal with lesquerella
Do research and development institutions exist that could assist the marketing of lesquerella?	No marketing support for lesquerella; developing information on the relationship with castor oil and other marketing information should not be difficult	Existing institutions will need both time and money to develop the market for lesquerella products	No marketing support for lesquerella exists now but it can be developed with a commitment from industry
Do government services and regulations exist that would affect the marketing of lesquerella?	Little government influence concerning marketing lesquerella at this time	Minimal government influence in the marketing area at this time	Federal use and stockpile policies and preferences for environmentally friendly products may affect the marketing of lesquerella
Other distribution considerations?	None to report	None to report	Reluctance to change and acceptance of such items as grease formulations by castor companies may constrain the distribution of lesquerella
Consumption subsystem			
Can processed lesquerella products compete in the market?	More work needs to be done but indications are that lesquerella products can replace castor oil products	It will be difficult for lesquerella to compete in the market against castor unless advantages and competitiveness can be clearly demonstrated	—
Can the industrial oilseed market sustain and absorb additional production?	Lesquerella may be able to replace other oils currently in use but expanding the market will depend on lesquerella's own merits	Market potential is unknown because no lesquerella market exists; little is known about supply or price and demand is implied from the castor oil market	Initially lesquerella will substitute for castor but with product R&D, the industrial oilseed market can expand
Can consumers be made aware of the advantages of lesquerella production?	The consumer for lesquerella production is the chemical industry, which is responsive to proven advantages	The educational process of making consumers aware of the advantages of lesquerella is not expected to cost much	The consumer for lesquerella production is the chemical industry, which needs to become aware of the advantages of domestic, renewable resources
Can the lesquerella commodity meet the diverse needs of consumers?	The early research looks very promising that lesquerella will be more versatile than castor oil in meeting needs in the chemical industry	The extent of diversity of lesquerella products still needs to be determined but the early research looks good in this area	The early research looks very promising that lesquerella will be more versatile than castor oil in meeting needs in the chemical industry

— = No summary statement included in the survey.

Table C2. Responses to Summary Statements by Participants in the Lesquerella Delphi Survey.

Component description	Technically possible		Economically feasible		Institutionally permissible	
	Agree	Disagree	Agree	Disagree	Agree	Disagree
Production subsystem						
Land allocation	15	0	11	4	11	4
Water allocation	13	2	13	2	12	2
Production financing	15	0	15	0	13	0
Pest control	11	3	14	0	10	4
Seed availability	12	2	13	1	na	na
Fertilizer availability	14	0	14	0	na	na
Input transportation and storage	14	1	14	1	na	na
Managerial ability	14	1	15	0	14	1
Production equipment	15	0	13	2	na	na
Energy availability	14	0	13	0	na	na
Input market information	14	1	15	0	na	na
Government services and regulation (production)	12	2	12	2	11	3
Production research	14	1	15	0	14	0
Information dissemination programs	13	1	12	2	14	1
Information exchange institutions	11	4	13	1	11	4
Farm labor needs	15	0	15	0	14	0
Market information for producers	13	1	11	4	14	1
Germplasm development	14	1	—	—	—	—
Commercialization prospects	8	7	—	—	—	—
Marketing subsystem						
Procurement resources	13	1	15	0	na	na
Dependable supply	13	2	14	1	na	na
Procurement financing	12	2	13	1	10	4
Government services and requirements (procurement)	12	3	10	4	10	4
Market information for procurers	12	3	14	1	na	na
Transportation and storage	12	1	12	1	na	na
Processing resources	14	1	14	1	na	na
Processing equipment	14	1	13	2	na	na
Information exchange institutions	14	0	13	0	14	1
Energy availability	14	1	14	1	na	na
Processing research	12	2	14	0	14	1
Information dissemination programs	13	1	10	5	9	4
Coproduct use	13	1	13	1	11	2
Managerial ability	13	0	12	1	na	na
Distribution resources	13	1	14	0	14	1
Distribution financing	9	2	14	0	10	3
Product market information	12	2	15	0	12	1
Product transportation and storage	14	1	14	0	na	na
Product R&D institutions	15	0	14	1	15	0
Market R&D institutions	11	4	14	0	15	0
Government services and regulations (marketing)	12	3	14	1	13	0
Consumption subsystem						
End-product competition	12	1	15	0	na	na
Market size	14	1	14	1	13	2
Consumer awareness	14	1	10	5	15	0
Product versatility	13	2	14	1	12	2

na = Not available.
— = Not applicable.